Report of the Commission of Inquiry on Aluminum Wiring

Part 2

J. Tuzo Wilson, *Commissioner*

March
1979

ONTARIO
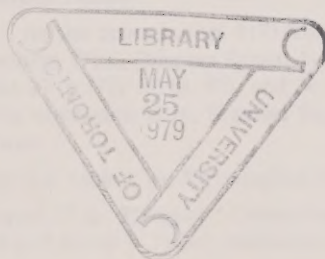
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Acknowledgements

The quotation on p. 22 is reprinted from Report on CPSC Public Hearings on Fire Hazards Associated with Electrical Wiring Systems Utilizing Aluminum Conductors [held in Los Angeles, Calif.]; the quotation on p. 94 is from Minutes of Aluminum Wiring Meeting [held in Washington, D.C.] Both the Report and the Minutes are publications by the U.S. Consumer Product Safety Commission.

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References to Sources

Detailed information on sources referred to in the text of this Report will be found in Sections 3.1 and 3.3. The Commission of Inquiry on Aluminum Wiring has made every reasonable effort to include all sources, and apologizes for any errors or omissions.

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For it is the essence of science, and common sense, to regard our present knowledge as subject to growth, addition or revision, and therefore — tentative. Otherwise we become prisoners of our yesterdays, stuck with our dogmas, mired in our inability to learn and adapt.

A group of prominent science writers recently formed an organization called "The American Tentative Society." The announcement of the formation of the Society included the above quotation to explain that its name had been selected deliberately and with care.

It seems appropriate to quote the view of these distinguished observers of science in order to emphasize that all technology, whether or not well-adapted and excellent at the time it was introduced, is subject to unending revision and improvement.

2.1   Legal Powers Regulating Residential Wiring

The regulation and control of safety in the electrical industry is a provincial responsibility and in Ontario is dealt with under the Power Corporation Act.* Under the provisions of the Power Corporation Act, Ontario Hydro is responsible for setting standards for such aspects as the design, installation, and proper operation of all work involved in the generation, distribution, and use of electric power in Ontario. Section 94 of the Power Corporation Act authorizes Ontario Hydro to appoint any person or association, having special knowledge and facilities, to inspect, test, and report on any related matters or works.

The Electrical Safety Code, a regulation under the Power Corporation Act, outlines the requirements for the approval, installation, and intended use of electric systems. The Code also provides that no person shall advertise, display, offer for sale, sell, or otherwise dispose of electric equipment unless it is approved. A product is deemed to be approved when the Canadian Standards Association issues an authorization report and the report is accepted by Ontario Hydro. Once approval has been granted, the manufacturer enters into a service agreement with the Canadian Standards Association and is permitted to affix a certification label to the product. Periodic testing is then performed to insure that the product continues to meet the required standards of design and construction.

In practice, Ontario Hydro inspects the design, construction, and installation of all residential wiring systems. Their powers to inspect and approve electric-wiring systems are restricted by the Electrical Safety Code to the aspects of the safety of the public and the protection of property, leaving factors of reliability largely to the market place. The result has been that Ontario Hydro and the Canadian Standards Association are concerned primarily with whether equipment fails in a safe manner in a given percentage of incidents. The distinction between safety and reliability was not defined clearly in the evidence of any of the witnesses who appeared at hearings held by the Commission.

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* In 1973 the Power Commission Amendment Act, R.S.O. Chapter 57, 1973, changed the title of what had been the Power Commission Act to the Power Corporation Act.

2.2 Brief History of Residential Wiring in Ontario

2.2.1 Developments Prior to 1965

Copper occurs both as a native element and as a constituent in other ores. Because it exists in a pure state or can be separated easily from other constituents, man has known and used the metal for various purposes throughout history. Since its electric properties are superior to those of other base metals, it is natural that, from its inception a century and a half ago, the electrical industry has used copper as a conductor.

Aluminum, or aluminium as it is sometimes spelled, does not occur as a native element. It was first identified in 1782 and separated only in 1825 by Hans Christian Oersted, a Danish physicist. The cost of separating the metal from its ore prevented any commercial applications until after 1886, when a cheap electric method of production was developed. The use of aluminum has expanded steadily ever since.

High-tension cables were first fabricated from aluminum in 1898. The relative cost of processing, fabricating, and installing aluminum and copper has been such that, for the past several decades, aluminum has replaced copper almost completely for high-voltage, high-current transmission of electric power. Trained electricians join large cables by applying pressures great enough to cause the metal to flow, thereby breaking oxide films, welding the conductors, and insuring good connections. At the same time, copper has continued to be used almost exclusively for light-current, low-voltage applications in electronics and telecommunications.

Immediately after World War II copper was scarce and aluminum was introduced for residential wiring in many countries. A variety of techniques were used, with results varying from failure to continuing successful use. In 1947 the Canadian Standards Association authorized the use of aluminum as an alternative to copper for residential wiring in Canada, initially with fully hard temper. Aluminum wiring was used very seldom at first except for its experimental installation in 1948 in seventy-five houses in Arvida, Quebec. Witnesses stated that the wiring in Arvida has performed satisfactorily since it was installed. In 1953 fifty homes were so wired in Kitimat, B.C.

Section 2.6 records how, over the next twenty years, both Canadian and American authorities monitored the situation without receiving any reports of appreciable problems with aluminum wiring.

2.2.2 The Situation from 1965 to 1976

In the mid-1960's, political problems in the largest copper-producing countries, Chile and Zaire, made copper an expensive and sometimes scarce material. This led to the introduction and extensive use of aluminum wire for residential branch-circuit wiring. No statistics have been kept in Canada of its use by year or by geographical location, but manufacturers of aluminum wire estimate from the sales of the grades of conductors used for residential purposes that the peak use of aluminum was reached in 1973 or 1974, and that aluminum wire was used in a total of approximately 250,000 dwelling units in Ontario and in about 200,000 more units in the rest of Canada.

At the time of large-scale introduction of aluminum into residential wiring systems, the regulatory agencies — Ontario Hydro and the Canadian Standards Association — were aware that copper and aluminum behave differently in electric circuits. Both agencies, for instance, specified that, to compensate for poorer conductivity, the gauge of aluminum wire should be heavier (for example, AWG-12 instead of AWG-14) than that of copper wire.

By 1966 electric utilities all over the world, including Ontario Hydro, had had several decades of satisfactory experience with aluminum conductors in high-power transmission circuits. Residen-

tial wiring circuits are, by comparison, low-power. Few of the agencies considered that the use of aluminum wire in residential circuits constituted any substantial risk, or that its introduction warranted any significant changes in devices or installation practices.

The Ontario authorities' confidence in aluminum wiring was increased both by the knowledge that a few houses in Canada had already performed without reports of trouble for about twenty years and by the results of tests, considered adequate at the time, which also gave no cause for concern.

The failures which began to be reported in the early 1970's, a few years after the new installations had been made, were clearly as unexpected by Ontario Hydro and the Canadian Standards Association as they were alarming to the householders concerned.

Such lack of foresight has been a common feature of developing technologies. Today the causes leading to trouble are clear but at the time they were not. In part the failures are due to disparities in the properties of aluminum and copper, some of a subtle nature, to which insufficient attention was paid; in part, the fact that two other factors of a different kind played a role. Early this century, when the present system of residential wiring was introduced, appliances were few and electric loads light. During the boom years when aluminum wiring was being introduced, appliances multiplied, placing greater loads on residential installations. Greater loads in turn generate more heat, to which aluminum conductors are particularly sensitive. The tests made between 1947 and 1967 were not sufficiently discriminating to take this characteristic of aluminum into account. The same boom also led to rapid construction of many homes and a concurrent shortage of experienced electricians in some regions; demand and competition favoured quick and, at times, shoddy work and the importation of devices not approved for use in Canada.

2.2.3   Actions by the Canadian Standards Association

After approving aluminum wiring for residential use in 1947, the Canadian Standards Association continued to monitor and test aluminum wiring. In 1967, upon finding difficulties in forming loops at binding-head screw terminations, the Canadian Standards Association made a recommendation that led Ontario Hydro to prohibit the use of fully hard aluminum wire and authorized only half-hard wire.

During 1968 the Underwriters' Laboratories, Inc. in the United States began to receive reports of problems in the use of aluminum wire. To solicit information, the Underwriters' Laboratories, Inc. and the United States National Electrical Association jointly sponsored a field survey. This survey was directed primarily to industrial and commercial users of aluminum wire, to electrical contractors, and to inspection agencies in the United States. Although the statistical validity of the results may be open to question, the survey showed that a higher proportion of terminations failed with aluminum conductors than with copper conductors. In Canada failures were first reported in 1972.

In October 1970, after having refused to do so for the first samples submitted, the Canadian Standards Association authorized the use with aluminum wire of one make of receptacle of the push-in type. Field experience proved that connections with receptacles of this type were particularly poor; in April 1974 the Canadian Standards Association again prohibited the use of these receptacles with aluminum wire. Since no records were kept of how many were sold, or where, the receptacles already installed could not be located and replaced. It was not possible to estimate the severity of the problem, and the public was not informed. To complicate matters, some other makes of push-in receptacles, which had not been authorized for use with aluminum wire, were in fact used with it.

Field reports also indicated that an undetermined number of wiring devices with steel terminal screws had entered the Ontario market. These screws were never authorized for use in Ontario, although they were permitted in the United States. In August 1974 the Canadian Standards Association issued a bulletin banning the use of steel screws for current-carrying terminals in switches and receptacles but permitting their continued use in ground circuits.

In May 1974 the Canadian Standards Association formed a Task Force on Aluminum Terminations, with members drawn from its own staff, the utilities, the electrical industry, and the Con-

sumer Association of Canada. In June 1975 the Task Force formed a smaller, technical Working Group. The recommendations for these two bodies soon produced changes.

In July 1975 the Canadian Standards Association approved the CO/ALR (copper/aluminum revised) preliminary standard for receptacles, which it had adopted from Underwriters' Laboratories, Inc. Receptacles designed to meet these requirements had come into use in the United States in 1972, but in Canada they did not become generally available until mid-1976.

In September 1975, as a result of the work done by its Task Force, the Canadian Standards Association banned zinc plating on current-carrying terminal parts of receptacles, plugs, switches, and lamp holders. The ban was reinforced in April 1977.

In April 1976 the Canadian Standards Association approved the CO/ALR specification for general-purpose switches for alternating currents, but in mid-1978 such switches were just becoming available in larger retail stores in metropolitan areas.

In November 1976 the Canadian Standards Association recognized the problems encountered with electric baseboard heaters in which extra-flexible copper wire was connected to solid-aluminum wire. In March 1977 the Canadian Standards Association specified that electric baseboard-heater connections should be marked for copper only.

In May 1977 requirements were adopted for special-service pigtail connectors for use with extra-flexible stranded conductors, but to date no Canadian manufacturer is marketing such devices in Ontario. As yet, there is no comprehensive system of terminations suitable for use with aluminum wire in residential circuits, and different approaches have been advocated in different parts of Canada. Presumably this not very satisfactory situation is only temporary.

The Canadian Standards Association has directed most of the information in its various bulletins and notices to electrical manufacturers and contractors. Until recently very little information was made available to householders, but the Association now publishes an information bulletin for the consumer entitled *CSA + the Consumer*. The February 1977 issue, Number 77-15, provided some information on aluminum wiring to consumers in general, although it was not directed specifically to householders who had aluminum wiring in their homes.

2.2.4   Actions by Ontario Hydro

In 1972 and 1973 Ontario Hydro began to receive reports of failures with pigtail connectors and at receptacle terminations. In the fall of 1974, it established an ad hoc committee and requested help from its research division. Since 1974 the W.P. Dobson Research Laboratory of Ontario Hydro has done extensive research on aluminum terminations for residential circuits and has made available much of this information to the Commission of Inquiry on Aluminum Wiring.

Ontario Hydro inspectors throughout Ontario made inspection visits to homes and took other actions in connection with residential aluminum wiring, but in different regions the inspectors handled the problems in different ways. Inspectors in Ottawa replaced failed receptacles and tightened loose connections. In their view, the main cause of failure was loose terminations due to poor workmanship. During 1974 and 1975, Ontario Hydro inspectors changed receptacles in over 200 residences in Ottawa. The inspection department in London, on the other hand, took the special step of warning the local contractors that, with aluminum wiring, the quality of workmanship was particularly critical. In January 1977 Ontario Hydro established in Brampton a special telephone service to advise householders about aluminum-wiring problems. The Commission was told that this service, called a *hot line,* has given advice to householders, told those living in homes wired with aluminum how to recognize warning symptoms, and informed them where to get a qualified electrician to inspect and, if necessary, to repair their wiring systems. Many members of the public have appreciated, and been reassured by, this helpful service.

In November 1975 Ontario Hydro prepared a special announcement to advise householders of symptoms that might warn them of an incipient electric failure. This announcement was made available to local utilities for distribution to householders in their areas. Not all utilities have done so, however.

2.2.5 Recent Actions of Municipal and Provincial Authorities

Certain municipal jurisdictions and some Ontario governmental agencies have also reacted to aluminum-wiring problems. For example, the Townships of March and Gloucester, near Ottawa, banned the use of aluminum wiring in new construction in their jurisdictions. In testimony to the Commission, representatives of these two townships indicated that they had no technical grounds or proven adverse experience within their jurisdictions to justify the ban. Media reports had indicated that some fires involving aluminum wire had not been explained and that an imminent hazard was associated with residential aluminum wiring. Hence the authorities were concerned about the safety of residents.

The Ontario Housing Corporation and the Ontario Ministry of Government Services also prohibited the use of aluminum wiring in residential circuits under their control. As reasons for their actions they stated that they found that the economic advantage of using aluminum in place of copper wiring was insignificant, that copper provided more nearly trouble-free maintenance, that CO/ALR-grade devices were not generally available throughout the province, and that CO/ALR-grade devices did not constitute a complete system for residential wiring.

There is no doubt that conflicting advice and actions by various governmental agencies coupled with exaggerated media reports have increased the confusion and worry of householders.

2.2.6 Activities of Associations of Householders

During the Commission's hearings in Ottawa, two witnesses, each representing a different group, were heard. Mr. B. Jerabek, an independent research analyst and consultant, stated that he was the President of Concerned Consumers Foundation Inc., which had been incorporated in February 1975 under a Federal charter. Mr. A. Sewards stated that he was a member of a small committee of volunteers formed in 1975 at the request of the Reeve of the Township of March at the time that the township banned the use of aluminum wiring in residences.

The Commission also heard evidence from the two co-founders, Messrs. G. Heighington and J. Murphy, and other members of a group of home-owners, many of them from Brampton. During the hearings this group styled itself the Aluminum Wiring Home Owners Association and stated that between five and six hundred membership cards had been issued to families. Nearly all live in Ontario, but a very few live elsewhere in Canada.

Messrs. Jerabek, Heighington, and Murphy have been active on behalf of concerned consumers and have appeared before various municipal councils in the Ottawa and Toronto areas. It is fair to say that these three have been instrumental in focusing public attention in Ontario on home-owners' problems with residential aluminum wiring, but they have also enlisted the support of two prominent Canadian scientists, Dr. P.D. McTaggart-Cowan and Professor Ursula Franklin.

At the hearings in Toronto, Brampton, and Scarborough, a number of householders came forward as witnesses. In Ottawa no householders except Messrs. Jerabek and Sewards, who represented the associations of householders, came forward. Although the Commission advertised widely, no householders elsewhere offered to give evidence.

2.2.7 The Situation in 1977 and 1978

During 1977 and 1978 the Commission devoted a year and a half to collecting evidence which showed that, in contrast to the slight use of, and lack of problems with, aluminum wiring that had prevailed up to 1965, there were many failures during the next decade, and that in Ontario aluminum-wired residential branch circuits were less reliable and probably less safe than copper-wired circuits. The difficulties were not universal. Most of the 250,000 homes equipped with aluminum wiring have experienced no problems, and the vast majority of owners did not approach the Commission. Nevertheless, in some cases the troubles have been severe.

This surprised everyone and led to the activities described in prior subsections. As subsequent sections of this report show, the causes and the resolution of the problems are not simple, but it is clear that a major cause — and probably the greatest single cause — is connections that have

not been adequately tightened. Evidence suggests that a strongly tightened connection may last indefinitely with both copper and aluminum and hence be reliable, that an extremely loose connection will fail quickly with either, and that a moderately loose connection — which probably would not be detected by a visual inspection — fails more quickly with aluminum wire. Aluminum wiring is also more sensitive to other forms of poor workmanship and to several devices, including steel screws, zinc-plated connections, and push-in connections; to all of these copper is more tolerant. These devices have now been largely corrected or banned and replaced, as the sale of about 1,500,000 CO/ALR receptacles suggests.

By the time the Commission met, these characteristics of aluminum wiring were understood, and many householders and electricians, the Canadian Standards Association, and Ontario Hydro had taken vigorous corrective action. As Mr. J. Murphy, a representative of one of the homeowners' groups, stated on October 12, 1977, "We know the problems and we know Ontario Hydro has done a lot of work." Mr. Murphy then made some recommendations, most of which have been acted upon already or are being put into effect.

The evidence shows that these corrective actions have been highly beneficial. Throughout the hearings the Commission felt that it was dealing with past rather than present troubles. Everyone involved naturally watched with concern for evidence of new failures and fires, but few were reported and the worst of those turned out to result from causes other than aluminum wiring. Inquiries to the Brampton hot line subsided. As Section 1.8 shows, there was a dramatic decline in calls upon the Electrical Inspection Department in Ottawa. A news release in August 1978, which received widespread publicity, resulted in only one request to the Commission and few to Ontario Hydro that were due to any problem with aluminum wiring. Except in the general vicinity of Toronto no individual householders came forward; of the two representatives of homeowners' groups heard in Ottawa, one expressed his surprise that so small a proportion of fires was electric in origin. Throughout the greater part of Ontario there was no evidence of much interest in the subject of the Inquiry.

Thus the Commission was forced to conclude that there had been real problems in some localities, but that these had largely been resolved before the Inquiry took place. In spite of this overall relief, the Commission is concerned about three remaining possible causes of difficulties in the future. First, the steady increase in demands for and use of electric power in homes means that the existing systems for copper as well as for aluminum should be scrutinized. The existing system was designed for use with copper wiring and will always be more subject to possible errors when aluminum wiring is used. However, even when used with copper wiring, it may fail when overloaded or abused. As the Commission heard, copper wiring also fails and causes fires. Vigorous attempts are under consideration and should be pursued to make home wiring even safer than it is, for unfortunately failures and fires do occur.

Second, there are probably some who are still unaware of potential hazards. The Commission recommends that publicity reach every home in Ontario to alert all to signs of possible dangers and to corrective measures.

Third, the evidence and letters received suggest that a few householders, who are aware of troubles, have taken either no action or inadequate action to correct what may be hazards in their homes. The terms of this Commission prohibit it from assessing any liability, but it does seem that, regardless of who was responsible for any errors which may have occurred, householders who know of potential hazards should seek advice and take corrective action with respect to their own houses. All these matters are dealt with at greater length in appropriate sections.

2.3 Description of the Residential Branch-Circuit Wiring System

The typical residential electric-wiring system consists of two parts: the supply service and the internal branch circuits.

2.3.1 Supply Service

Electric power is carried from the utility's network system to the consumer's service equipment by supply-service conductors that may be installed either overhead or underground. The conductors terminate at the main switch of the consumer's service-entrance panelboard, which also contains the branch-circuit panelboard. The utility also installs a revenue meter near the entrance.

Most electrical utilities supply residential units with either a 120/240-volt or 115/230-volt, single-phase, three-wire, 60-cycle, alternating-current system. The supply services are usually rated 60-, 100-, or 200-ampere capacity, depending on the floor area of the home and the nature of the intended electric loads.

2.3.2 Branch Circuits

Within a residential unit, branch circuits supply electric power from the service-entrance panelboard to the various points of utilization. Branch circuits are defined as that part of the wiring installation between the branch-circuit fuses, or circuit breakers, in the service-entrance panelboard and the various outlets. The power-consuming appliances or equipment connected to the outlets are not considered part of the branch circuits.

The outlets provided in residential units are either receptacles or of the direct-connection type. Receptacles provide power for such free-standing appliances as electric cooking ranges, refrigerators, and clothes dryers, and for such portable appliances as vacuum cleaners, television sets, and hair dryers. Direct connections provide power to fixed equipment; for example, fixtures mounted on ceilings or walls, baseboard heaters, furnace motors, and built-in dishwashers.

A branch circuit is classified as specific or general depending upon whether it supplies one or several outlets. Specific types are provided for electric cooking ranges, clothes dryers, refrigerators, furnace motors, built-in dishwashers, and similar types of appliances. Hence, we often hear such expressions as *dishwasher circuit* or *furnace-motor circuit.* Where homes use electric heating, separate branch circuits are provided to which may be connected only outlets supplying such heating units as baseboard and convector heaters. These branch circuits also are called *specific* whether they supply one heating outlet or several. Depending upon the electric loading, specific branch circuits are normally rated at 15-, 20-, 25-, 30-, 35-, 40-, or 50-ampere capacity.

In Ontario, general branch circuits are rated at 15-ampere capacity. Any one circuit usually supplies a combination of duplex receptacles and direct-connection outlets. These outlets normally are located in several different rooms and may even be on different floors within the home. Receptacles are also provided above the kitchen counter. The increased use and simultaneous operation of several portable electric cooking appliances have resulted in many kitchen circuits being overburdened, causing the branch-circuit overcurrent-protection devices to operate. To rectify this problem it was decided to make it possible to split or electrically isolate each section of a standard duplex receptacle and connect a specific branch circuit to each section. Such an arrangement is called a *split receptacle.* Figure 1 shows the wiring devices and wiring cables in a simplified model of a residential branch-wiring system.
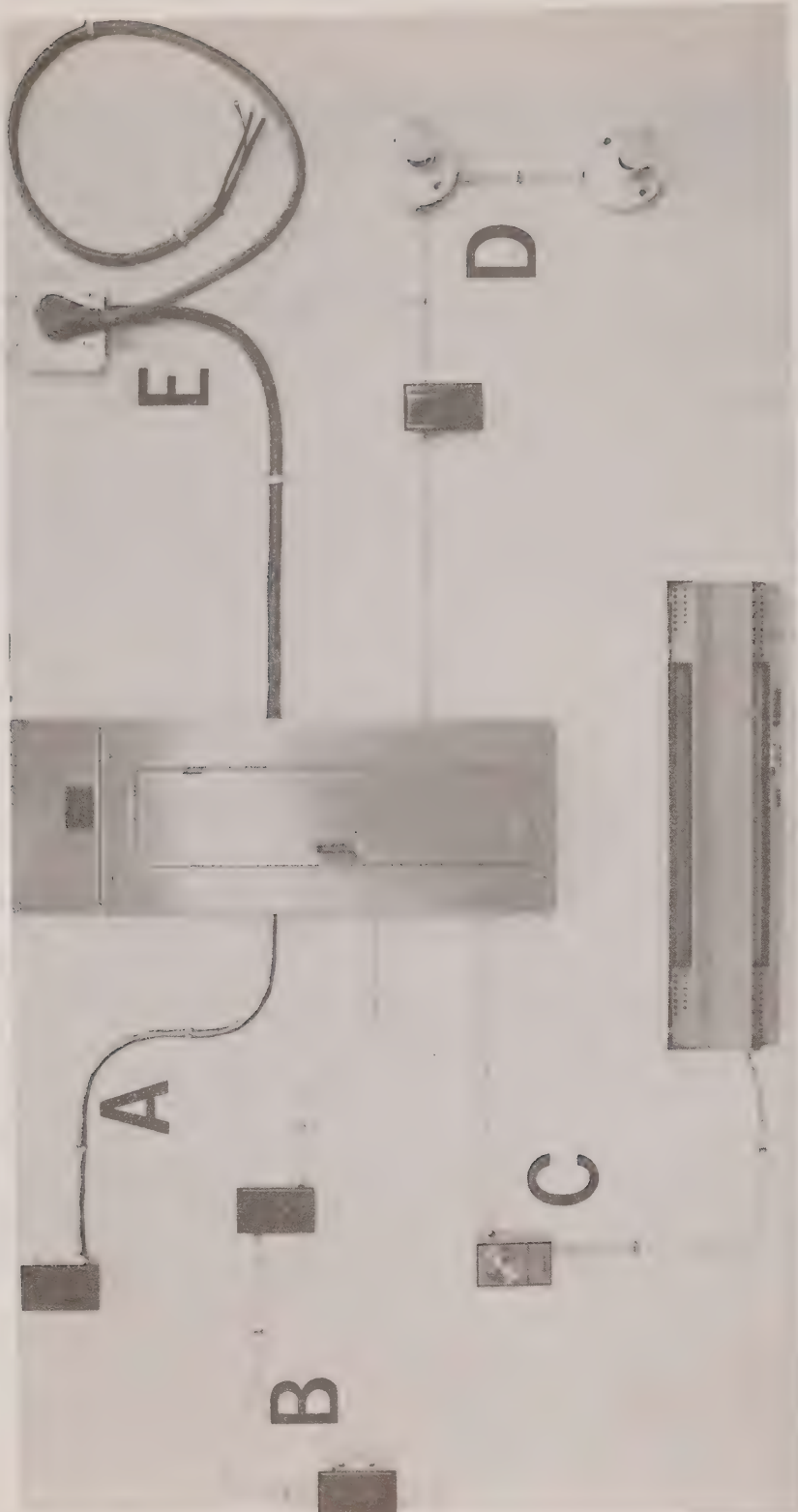
Figure 1. Simplified Model of a Residential Branch-Circuit Wiring System

Specific types of branch circuits are:

Circuit A, a split receptacle supplied by a two-circuit cable
Circuit C, an electric baseboard heating unit with a remote-control thermostat supplied by a single-circuit cable
Circuit E, a heavy-duty receptacle suitable for an electric cooking range, clothes dryer, or other heavy-load appliances supplied by a two-circuit cable

General types of branch circuits are:

Circuit B, which supplies duplex receptacles
Circuit D, which supplies lights through a switch

Normally, circuits B and D would have a combination of receptacle outlets and lighting-fixture outlets connected to them.

2.3.3 Design of Residential Wiring Systems

Residential wiring systems are usually designed to consist of three sections: the first to provide the minimum amount needed to satisfy the Electrical Safety Code requirement; the second to service any equipment provided above this minimum; and the third to provide for future services. The latter two sections may be supplied in a limited amount or not at all, because the future service requirements of the original and subsequent home-owners are unknown and because the builder must compete in a highly competitive market.

For apartment buildings a professional electrical engineer usually designs the electric system. Because governmental agencies are involved, he prepares detailed design drawings which show the approximate location of the various outlets in the dwelling units and the circuits to which each outlet is connected. These agencies and companies normally require a design that is more stringent with respect to flexibility of usage, convenience in location, and capacity for future needs than the Electrical Safety Code stipulates.

In single-family dwelling units professional electrical engineers are not usually retained to prepare the design, but the builder enters into a contract with an electrical contractor to design a system that will meet the requirements of the Electrical Safety Code and to install it in a manner that will satisfy the Electrical Inspection Department of Ontario Hydro. Sometimes the architect indicates on his plans the location of lighting-fixture outlets and their respective control switches, but the electrical contractor normally does not make a drawing of his design.

Revisions in the current (1977) edition of the Electrical Safety Code have made the requirements for branch circuits in houses similar to those specified for apartments. The requirements are now more stringent in respect to the location and convenience of receptacle outlets, but the Code still does not require drawings of the circuitry or records of how the wiring system is connected in single-family dwellings. Different tradesmen often wire general branch circuits differently.

2.3.4 Overcurrent Protection

The Electrical Safety Code requires that branch circuits be provided with overcurrent-protection devices that will automatically isolate the circuit if the current flowing through it reaches a value that produces dangerous temperatures in the conductor or in apparatus connected to the circuit. The normal types of overcurrent-protection devices used for residential branch circuits are fuses and circuit breakers.

When a conductor carries an electric current, heat is generated in direct proportion to the resistance of the conductor and to the square of the current. The Electrical Safety Code specifies the maximum safe current that a conductor may carry without overheating. This specified current depends upon the size of the conductor, the type of metal used in the conductor, and the type of insulating material around the conductor. When this value of current is exceeded, the circuit is said to be overloaded and the overcurrent-protection device should operate and isolate the circuit.

Overloading normally results from the connecting of too many appliances to a circuit. Overloading may also be caused by motors starting improperly or starting and stopping too frequently. When an electric motor starts from rest, the starting, or inrush, current which flows is several times the normal current when the motor is running at full load. As the motor gains speed the inrush current decreases to the normal running value.

Overcurrent-protection devices also provide protection against fault currents. Fault currents may reach values of several hundred to a few thousand amperes in residential circuits. Fault currents normally are classified as short circuits or ground faults. A fault current flows when an accidental contact of line-to-line or line-to-neutral conductor causes a short circuit. A ground fault current flows when the line makes an accidental contact with a grounded non-current-carrying metal part, such as the body of an electric kettle.

2.3.5   Fire and Safety Hazards of Electric Systems

If properly designed, installed, and maintained, residential electric systems for lighting, heating and cooling, cooking, and other purposes are convenient and safe. If such systems are not installed and maintained properly, they may introduce hazards of both fire and personal injury.

Electricity may create a fire hazard through arcing or through overheating of electric equipment. An arc is produced when an electric circuit carrying a current is interrupted either intentionally, as by a switch, or unintentionally, as when a contact at a terminal becomes loose. A high-resistance connection may generate heat. The intensity of the arc and the degree of heat depend largely on the current and the voltage of the circuit. The temperature reached by the heating may be high enough to ignite any combustible material in the vicinity, for example, the insulation and covering of the conductor. An electric arc may not only ignite combustible material in its vicinity, but it also may fuse the metal of conductors. In residences a potential hazard exists from the possibility that hot sparks from burning combustible material and hot metal may be thrown or expelled from a junction box and come in contact with and set fire to other combustible materials, such as broadloom, newspapers, or curtains.

Electricity presents a personal-safety hazard directly through burns and shocks and also, indirectly, as a result of a shock, through falls, drownings, or self-inflicted wounds from circular saws or other devices. Shocks can result from contact with live parts or can be received when contact is made with metal parts of appliances that normally do not carry current but that have been energized through fault conditions and do not have adequate grounding protection.

2.3.6   Residential Wiring-System Components

The Canadian Standards Association must certify and approve all wiring devices, conductors, and panelboards that form the component parts of a residential wiring system. Some common component parts are as follows:

a.   Light Switches. Switches close or interrupt the electric current in a line conductor to the remainder of the circuit. Those used in homes are usually single-pole toggle switches, normally rated for 15-ampere operation. Figure 2 shows a typical toggle switch with conductors terminated in binding-head screw terminals on one side.

b.   Outlet Boxes. Such wiring devices as toggle switches and receptacles must be installed in outlet or junction boxes. Some of these boxes are more shallow than others. They are usually, but not always, of metal and may be either mounted on, or recessed into, a wall; they also are installed in the ceiling to house the wiring connections of lighting fixtures. Outlet boxes are also used to house cable connections, splices, and junctions in a circuit.

When used with wiring devices, a cover plate over the front of the box permits operation of the device but prevents accidental contact with any live parts.

Figure 2. Toggle Type of Lighting Switch

Figure 3. 15-Ampere Duplex Receptacle

c. *Receptacles.* Figure 3 illustrates the 15-ampere duplex receptacle, the most widely used receptacle in a home. Since several receptacles may be connected to the same circuit, the standard duplex receptacle is designed to allow current to flow through it to the other receptacles. When so used, the incoming wire is attached to one screw of a current-carrying terminal and the outgoing wire to the other terminal screw. Current to downstream receptacles passes from one screw to the other through a metal break-off tab, which connects the two screw-terminal pads. When it is desired to use a duplex receptacle as a split receptacle in order to increase the power capability, the break-off tab is cut and removed, thus isolating the two halves of the receptacle. Figure 4 illustrates a split receptacle with the break-off tab removed.

Figure 4.   Duplex Receptacle with the Break-off Tab Removed

Receptacles are provided with two current-carrying terminals, namely, the line and the neutral. The neutral terminal is identified with a light-coloured plated coating of cadmium, indium, silver, tin, or zinc (zinc is no longer permitted). The third terminal on a receptacle is the ground terminal, which, except for such abnormal conditions as ground faults, does not carry current.

Figure 5 shows a receptacle of the push-in type. Such a receptacle does not use a screw terminal connection; instead, the wire is stripped and pushed into a hole in the back of the receptacle. A metal spring inside captures and retains the wire. The spring will only release the wire when an external force depresses it.

Figure 5.   Duplex Receptacle with Push-in Type Terminals

d.   *Lighting Fixtures.* Ceiling-mounted lighting fixtures have screw terminals or are pre-wired with flexible copper-stranded leads. These copper leads are connected to the branch-circuit wiring with barrel or twist-on connectors, as shown in Figure 6.

Figure 6. Lighting Fixtures with Pre-wired Leads Connected to the
Branch-Circuit Wiring Using Pigtail Connectors

e. Baseboard Heaters. Baseboard heaters are controlled by an internal, or a remotely mounted, thermostat. The branch-circuit wiring is connected with approved connectors to the extra-flexible copper leads of the heater circuit. Figure 7 shows the wiring connections.
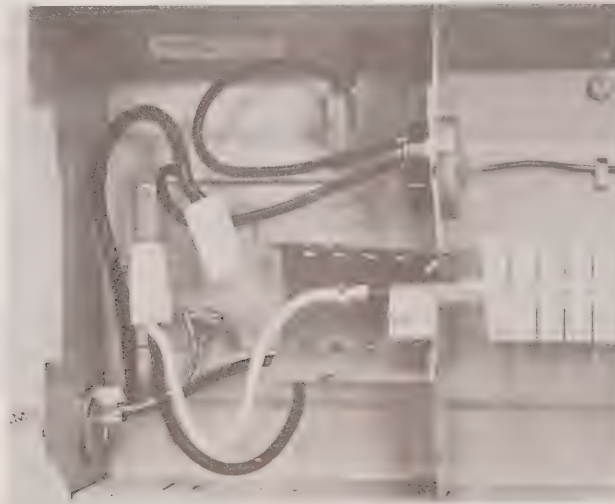
Figure 7. Typical Wiring Connections for a Baseboard Heater

f. Service-Entrance Panelboards. Figure 8 illustrates a service-entrance panelboard. The incoming main circuit-breaker switch controlling the supply service is located in the top compartment. Branch-circuit fuses may be of either the plug type or the cartridge type. Plug fuses normally are used for 15- to 30-ampere circuits.
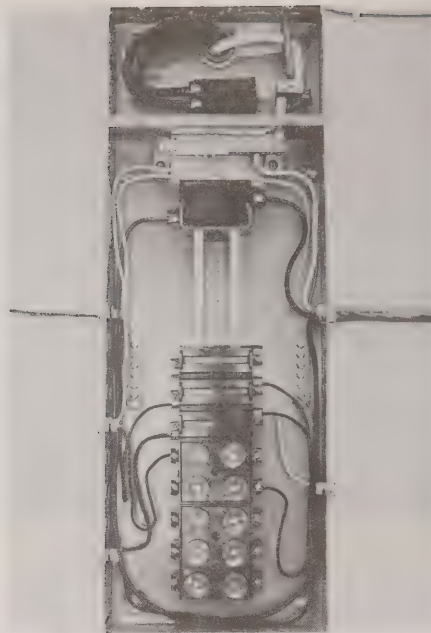
Figure 8.   Interior of a Service-Entrance Panelboard

g.   *Wire and Cable.* Most cables used for branch-circuit wiring are of the two- and three-conductor, non-metallic, sheathed type. The cable has either aluminum or copper wires with poly-vinylchloride (PVC) insulation and an overall jacket of moisture-resistant and flame-retardant braid covering the conductors and ground-wire assembly. The normal size of conductor is AWG-14 copper or the equivalent aluminum AWG-12. The AWG-14, -12, and -10 conductors are single solid wires.

Heavy-duty circuits use cables with stranded-wire conductors. Figure 9 illustrates examples of a non-metallic, sheathed cable and a stranded conductor.

NMD-7 90C 300V AL-FLEX
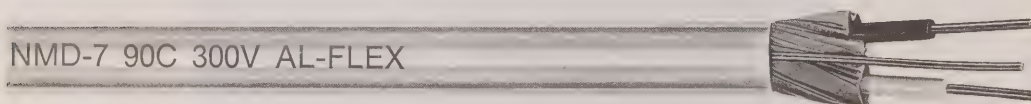
Figure 9A. Non-metallic Sheathed Cable Conductor Used in Residential Wiring

TWH 75C 600V

Figure 9B. Stranded Conductor Used in Residential Wiring

2.3.7 Wiring Terminations and Connectors

Branch-circuit wiring is normally terminated on devices by one of the following methods:

a. *Push-in Connectors.* Figure 10 illustrates this type of connector, in which the conductor is clamped against the terminal pad by a metal spring. In Ontario this type of connection is now permitted only for solid-copper conductors, although between 1970 and 1974 it was also approved for terminating solid-aluminum conductors. Terminations of the push-in type are used chiefly in receptacles.

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Figure 10.   Push-in Type of Terminal Assembly

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Figure 11.   Section Through a Binding-Head Screw Terminal

b. *Binding-Head Screws.* A termination with binding-head screws is the commonest type for branch-circuit conductors. Figures 2 (p. 11) and 4 (p. 12) show typical terminations. The Electrical Safety Code requires that aluminum conductors be wrapped about a screw in a clockwise

direction for three quarters of a complete loop and the screw tightened. The same procedure is considered good practice for terminating copper conductors, but it is not mandatory. Figure 11 shows a sectional view through a binding-head screw, terminal pad, and a solid-wire loop. Receptacles sometimes are provided with a combination of push-in and binding-head screw terminals, as shown in Figure 12. A receptacle contact is also illustrated, showing the two binding-head screw terminals, the two push-in terminals with a wire connected in one, the two receptacle female-blade contacts, and the break-off tab which provides the feed-through feature.

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Figure 12.   Duplex Receptacle with Combination Binding-Head Screw and Push-in Terminals

Also shown is a receptacle contact with a conductor connected in one of the push-in terminals.

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Figure 13.   Example of a Mechanical Set-Screw Connector

c. *Mechanical Set-Screw Connectors.* Figure 13 illustrates this type of connection, which is used mostly for terminating stranded conductors. Figure 14 shows a sectional view. Solid conductors may also be terminated in mechanical set-screw connectors. This type of connector is used normally on circuit breakers, fused disconnect switches, panelboard neutral blocks, etc.
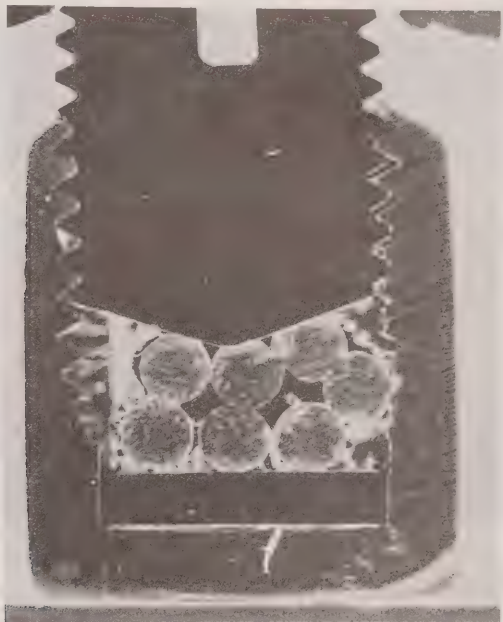
Reproduced with the permission of Ontario Hydro

Figure 14.   Section Through a Mechanical Set-Screw Connector

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Figure 15.   Twist-on and Set-Screw Types of Pigtail Connectors

d. *Pigtail Connectors.* These normally are used when conductors have to be spliced or connected together. Figure 15 illustrates two types of pigtail connectors, namely, a twist-on type and a set-screw type. The twist-on type consists of a coiled spring encased in a plastic holder. The set-screw type has a barrel with a set-screw and plastic cover.
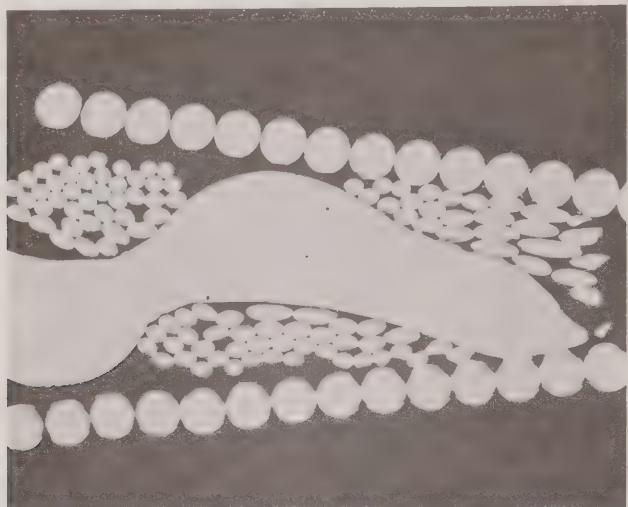
Figure 16.   Section Through a Twist-on Type of Pigtail Connector

The section is of a connection of a solid-aluminum wire and extra-flexible stranded copper wire. The cross section of the coiled spring in the connector is also shown.
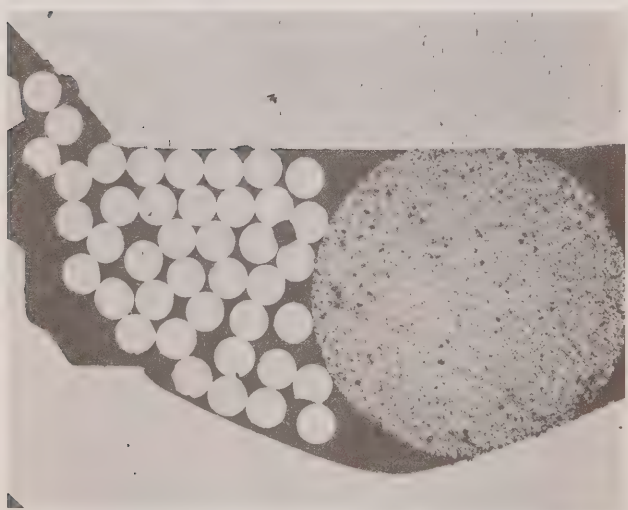
Figure 17.   Section Through a Set-Screw Type of Pigtail Connector

The section is of a solid-aluminum wire and extra-flexible stranded copper-wire connector.

Figure 16 shows a sectional view of a twist-on type of connector with a solid conductor and an extra-flexible stranded-copper conductor connection, such as would be used for making baseboard-heater terminations, etc. The coiled spring has traditionally been made from ferrous metals. The Electrical Safety Code currently has banned the use of twist-on connectors with ferrous-metal coils for connecting solid-aluminum conductors and extra-flexible copper-stranded conductors. Twist-on connectors with non-ferrous metal coils are permitted.

Figure 17 illustrates a sectional view of a set-screw connector with a solid conductor and an extra-flexible copper-stranded conductor. This type of connector likewise has been banned for use as a connector for joining a solid-aluminum conductor and an extra-flexible copper-stranded conductor.

2.3.8 Inspection and Testing of Residential Wiring Systems

In Ontario the Electrical Safety Code prohibits the connection of an electric installation, or of any part of it, to an electric supply until the installation has been inspected and approved by the Ontario Hydro Electrical Inspection Department. The person responsible for obtaining this inspection and approval is the electrical contractor. The term *electrical contractor* means a licensed contractor, electrician, or any other person who performs any work with respect to any electric installation or any other work within the jurisdiction of the Electrical Safety Code.

To obtain an inspection of a new wiring system, the electrical contractor must file with the local inspection department a completed application for inspection of the work before or within forty-eight hours of commencing work on the system. To modify an existing system, the contractor must apply for, and obtain, inspection of the work prior to energizing the additional or modified wiring.

The contractor is not required to submit plans showing the layout of the proposed electric wiring or specifications of materials along with the application for an inspection permit for electric work in single-family dwelling units. Plans and specifications must be submitted for a wiring installation in public buildings, commercial or industrial establishments, apartment houses, or other buildings in which public safety is a concern.

When the Electrical Inspection Department has inspected the new installation and found that it conforms with the Electrical Safety Code requirements, the department issues a connection authorization, with respect to the inspected installation, which permits the local electric utility to energize the installation. Where the installation is a form of modification to existing work, the connection authorization to energize and use the work is issued to the contractor.

The following is the usual procedure for the application for, and inspection of, a new single-family dwelling unit:

a. *Application for Inspection.* The electrical contractor makes an installation-inspection application with the authorities and pays the necessary fee, before or within forty-eight hours of commencing work at the site.

b. *Rough-in Inspection.* An inspector makes a first, or rough-in, inspection. At this stage of construction, the various junction and outlet boxes and interconnecting branch-circuit wiring have been installed, but none of the exterior siding, thermal insulation, or interior drywall or other wall-covering material has been installed. The inspector inspects the installed work to see that the wire and boxes have been installed correctly, and generally checks the wiring system for use of the correct size and type of cables, the number of branch circuits provided, and the number of outlets per circuit. The Code requires that no part of a wiring system may be covered up and hidden from view before it has been inspected. If the inspector deems that the electric installation is satisfactory, he gives permission to cover it up.

The inspector notifies the electrical contractor regarding any defects that are found in the wiring installation. When the contractor has corrected the defect, the inspector re-inspects the affected area of the installation. If he is satisfied with the repairs, he gives permission to cover up the installation.

c.   Inspection for Temporary Power. The next inspection is optional and usually is requested by the contractor when he wishes to have a temporary electric-power supply connected to the service-entrance panelboard. This allows temporary lights and power outlets to be provided to facilitate work on the structure. At this stage of construction, the service-entrance panelboard and associated service-entrance conductors must be installed and connected. If the inspector is satisfied with the electric work, he grants permission for a temporary service supply to be connected and energized.

d.   Final Inspection. The next and final inspection is when all of the wiring devices have been installed and connected, the cover plates have been installed, and the contractor has informed the inspection department that the work has been completed.

The inspector, at his own discretion, examines several devices by removing the cover plates and checking for the Canadian Standards Association approval insignia and the type and rating of the device, and visually examines the wiring connections. He also inspects the panelboard for its branch-wiring connections and verifies that two pole circuits have been provided with two pole fuses or circuit breakers, that the fuses or breakers are the correct rating, and that the panelboard-circuit identification card has been filled in. Should he decide that the installation is safe and complies with the requirements of the Electrical Safety Code, the inspector issues an authorization to permit the supply service to be connected and energized. If there are defects in the work, he withholds the authorization for connection until the contractor has corrected the defects and he has inspected the corrected work.

At his discretion, the inspector may perform the following tests:

(i) Ground-Continuity Test. This test is performed to make sure that items that should be grounded are indeed so. If electric power is available, the inspector uses a neon tester to verify the ground connection. If electric power is not available, he uses a flashlight and battery with test leads to verify the connection.

(ii) Receptacle-Polarity Test. This test is performed to ascertain that the receptacles are wired and connected properly to the line, neutral, and ground conductors. Electric power must be available at the panelboard to enable the inspector to use his receptacle-polarity tester to perform this test.

2.4   Summary of Technical Assessment

The Commission of Inquiry on Aluminum Wiring soon discovered that the differences in relative safety and reliability between aluminum-wired and copper-wired circuits are not simple but are influenced by subtle variations and small changes in circumstances which can have large effects. In order to understand the various causes of failure or lack of failure and to make soundly based judgements upon what to recommend, the Commission found it essential to explore several technical matters in some depth. Without this knowledge a generalization based on particular cases could be quite misleading.

Most of this information was not known when aluminum wiring was introduced, but since that time a great deal of knowledge and experience has been accumulated. Various aspects of the technical investigations of available data undertaken by the Commission are described in Sections 2.5, 2.6, and 2.7 which follow. Because the technical findings were both long and complex, some salient points are summarized in the subsections of this chapter.

2.4.1   Experience with Residential Wiring Systems in Ontario

The following points were made by householders, inspectors, and other witnesses at the hearings of the Commission:

a.   The use of high-power appliances in Ontario homes is increasing. There are indications of overstressing (for example, fuse-blowing, overfusing) in some circuits in residential wiring systems, whether with copper or aluminum conductors.

b.   Many appliances take surge currents that are high and cyclic. These currents may reach a 75-ampere peak value for short durations. Air conditioners, which are not always connected to individual circuits, are a common example.

c.   Certain designs of panelboards show higher failure rates than others.

d.   Many home-owners do not tighten their fuses adequately.

e.   The field evidence suggests that the actual measured values of installation torques for pigtail connectors are significantly lower than anticipated and are lower than those used in certification tests by the Canadian Standards Association.

f.   Duplex-receptacle connections can loosen when a wired receptacle is pushed back into an outlet box. The extent of this loosening is greater with non-CO/ALR devices and for lower values of initial torque.

g.   Residual torque on screw connections is likely to be higher where working conditions are favourable (for example, at a panelboard) than those under other conditions.

h.   In the field, the average electrician finds the making of proper planar three-quarter loops with AWG-12 aluminum conductors more time-consuming than making connections with AWG-14 copper wire. In the laboratory, a special jig is used to make standardized loops. Figure 11 ilustrates one such connection made in a research laboratory. It appears that the loop is not planar.

i.   A typical householder does not know the layout of the wiring system in his house (for example, the number of outlets on each circuit) or the appropriate fuse sizes. The vendor provides no information on fuse size or on the number and location of outlets on a given circuit. The householder learns this information by trial and error. A wiring diagram could be useful to him and in the initial design, in inspections, and in possible extensions of the wiring system.

j.   Overheating of device terminations of either copper or aluminum conductors, under certain combinations of circumstances, can become fire hazards.

k.   The present lack of interchangeability of wiring devices for aluminum wire is a potential cause of misapplication in residential circuits and hence a potential hazard.

l. The level of workmanship is a crucial issue. No evidence was presented to the Commission that suggested that the level of workmanship in the field is *purposely* poorer for aluminum wiring than for copper wiring. In this respect, the Commission has noted the statement made by W.H. Abbott of Battelle Columbus Laboratories (Battelle Institute), Columbus, Ohio, U.S.A., during an April 17-18, 1974 public hearing, held in Los Angeles, California, of the Consumer Product Safety Commission of the United States:

> The Washington testimony gave the impression that connection failures are due almost entirely to something called poor workmanship — specifically loose screws. This condition does cause failure but it does not present the total picture of termination problems.
> Loose screws cause failures for both copper and aluminum. They characteristically fail rapidly as part of an early failure distribution. We know of no significant difference between copper and aluminum in their propensity for failure with totally loose screws. In other words, if this condition is prevalent in the field, we see no basis for expecting different early failure distribution between copper and aluminum.

2.4.2 Laboratory and Field Studies on Aluminum Terminations in Residential Wiring Systems

The topics in this section are some of those covered in laboratory studies and field reports placed before the Commission.

a. Properly made connections of aluminum or copper wire under a binding-head screw at a torque of greater than 12 lb-in or in a compression lug will give reasonable performance over a long life, regardless of the screw material or coating.

b. Nominally tight 6 lb-in steel binding-head screw connections that are used with aluminum conductors overheat more frequently than those used with copper conductors. In fact, laboratory tests indicate that under identical experimental conditions binding-head screw and pigtail connections made with copper to copper or to brass perform better — as shown by contact resistance and temperature rise under current cycling — than those made with aluminum to copper or to brass.

c. The life of a binding-head screw or twist-on pigtail connection is critically dependent upon the residual-contact pressure. Small changes in this pressure make very large differences in the performance of a connection.

It is crucial to keep a contact interface stationary after a good contact has been made. Any factor (for example, vibration, insertion and removal of plug, pushing a receptacle back into the outlet box, etc.) that helps to loosen a contact, must be either completely eliminated or its effect minimized. In receptacles, a well-designed mechanical restraint feature for the wire and some feature for visually inspecting a binding-head screw connection for its tightness, could significantly enhance their reliability.

d. Zinc is a very poor plating material for contact applications.

e. There is some doubt about the long-term behaviour of indium platings in residential wiring devices, even with a nickel-barrier layer. At present, tin appears to be the favoured plating material, but almost all the CO/ALR devices made in the past and many in current production use indium as a plating material.

f. Normal 15-ampere fuses in residential use may not blow until a current of 17 to 18 amperes is reached.

g. The break-off tab is the hottest segment of a receptacle and contributes significantly to temperature rise of the current-carrying terminals in a receptacle. In a domestic-grade receptacle installed in an insulated wall and running at a current of 18 amperes, the temperature of the break-off tab may reach 70°C. to 75°C.

h. There are numerous differences in the physical and mechanical properties of aluminum and copper which make them behave quite differently in electric contacts. For example:

The differences between the coefficients of thermal expansion of steel and of aluminum are sufficient to loosen an aluminum-to-steel binding-head screw contact over a certain number of thermal cycles. This effect is less important for a copper-to-steel contact system and of little significance for a copper-to-brass contact system. The number of thermal cycles needed to loosen will depend upon the contact pressure.

The surface oxide film on copper conductors behaves quite differently from the oxide film on aluminum conductors. In the first place, there are several orders of magnitude difference in resistance of the two oxides. Second, the oxides of copper, unlike aluminum oxide, have a negative temperature coefficient of resistance. Third, there is some experimental evidence to suggest that the solubility of copper oxide in copper increases with temperature; on the other hand, aluminum oxide is not soluble in aluminum.

In branch circuits wired with aluminum and connected to brass, copper, or steel, it has been estimated that the relative motion resulting from differential thermal ratcheting could cause fretting failures. The hard oxide particles on aluminum make this metal particularly prone to fretting damage.

In view of these differences it is very likely that copper-to-brass connections behave quite differently than aluminum-to-brass connections when fretting corrosion sets in. Even when there is no motion but the contact pressure is low (for whatever reason), the oxidation or chemical corrosion of metal-to-metal contacts, or a-spots, is likely to be faster in aluminum-to-brass contacts than in copper-to-brass contacts.

i.   The various deterioration processes accelerate with temperature. For example, the time taken for the growth of a certain thickness of intermetallics at an aluminum-to-brass contact reduces dramatically from thirty years at 90°C. to about five years at somewhat over 100°C. Any design feature that reduces the operating temperatures in a device is a good feature.

j.   A surprising fraction of current (75% to 80%) in a binding-head screw connection appears to flow from the wire to the screw head and then to the receptacle base plate instead of from the wire directly to the plate. The contact interfaces involved in the current path through the screw head are not adequately designed to conduct current and are likely to be very susceptible to vibration and mechanical shock.

k.   When a wiring device fails through overheating, normal overcurrent-protective devices (fuses) do not always operate.

l.   The common signs warning that a failure by overheating is imminent are flickering lights, static on the radio, smell of burning insulation, occasional sparks from receptacles, inoperative receptacles, and hot or discoloured receptacle cover plates.

m.   The creep and relaxation behaviour of copper, of EC-grade aluminum, and of the new aluminum-conductor alloys are quite different. Some new alloy-conductor materials and copper show very little difference with respect to creep, and the maximum loss of contact force due to this process over a ten-year period is between 25% and 30%. With EC-grade aluminum, with temper from H16 (three-quarter hard) to H19 (full hard), contact-force reductions of 60% to 70% are possible under some circumstances in two to three years.

n.   Although the reasons for the superior performance in wiring-device connections of aluminum-alloy conductor materials, as compared to most of the EC-grade aluminum, are not understood precisely, some experts are of the opinion that the surface films formed on the new alloy conductors are quite different and are easier to break through when a connection is made.

o.   Failure mechanisms operating in residential wiring devices in the field are not clearly understood because insufficient research has been done to correlate laboratory experiments with field performance. Notwithstanding the lack of complete understanding, the following observations may be made:

(i) If a high contact pressure is continuously maintained on an initially well-made contact, the life of both copper- and aluminum-wire terminations in residential wiring is expected to be reasonably long (twenty to thirty years at the least).

(ii) When the contact pressure is lowered, for whatever reason, but the contact is nominally tight, several degradation processes come into operation. In the first place, there can be slow ingress of oxygen and other corrosive vapours (e.g., hydrogen sulphide, chlorine, water vapour), which gradually destroy the a-spots. It has been found that the contact remains stable untill the number of active a-spots has been reduced to a critical quantity. At this stage any further deterioration escalates catastrophically. Secondly, microscopically small motion at the contact interfaces (between strands of stranded-wire cables, between wire and plate, between wire and screw, or between screw and plate) can cause failure of a-spots, given sufficient time or enough cycles. The differences between copper- and aluminum-conductor materials noted

above make the two materials behave quite differently. In laboratory tests with fretting corrosion, aluminum has been found to be less forgiving of motion than copper. It appears that, at the same contact pressure, copper may withstand five to ten times as many cycles as aluminum before failing; to prevent motion, a tighter force must be maintained on an aluminum-wired system. To summarize the behaviour in another way, a wiring device that is designed to prevent motion in service will, for practical purposes, never fail. If motion occurs, failure will always occur eventually in the following order: first, a device connected to bare-aluminum wiring; second, to nickel-plated aluminum wiring; and last, to copper or copper-clad aluminum wiring.

p.   The objective for the design of a reliable wiring device must be to insure that either microscopic motion does not occur, or that a sufficient force and suitable materials are used to delay failure beyond the useful life of the connection system.

2.5   Contact Theory and Practice for Aluminum and Copper Conductors

This section introduces aluminum and copper as electric-conductor materials and reports some experience with aluminum conductors for residential branch-circuit wiring. Fundamental contact theory and service and testing experience with electric contacts are reviewed. The section concludes with a description and a discussion of contact degradation and failure.

2.5.1   An Introduction to Copper and Aluminum Conductors

a.   *Copper Conductors.* Copper is one of the seven prehistoric metals, which include silver, gold, iron, mercury, lead, and tin. Copper wire traditionally has been used for electric conductors for power transmission and distribution at high voltages and currents, for telecommunications at low voltages and currents, and for branch circuits operating at 120/240 volts and 15 to 30 amperes. In all these applications copper wire has performed well. However, problems have been reported, such as failures due to burn-out of connections in power-transmission lines, development of excessive noise in communications circuits, and connector failures in branch circuits.

In general, experience with copper in branch circuits has been considered acceptable. Failures usually occur at joints where extra resistance can be introduced into the circuit, and are generally attributed to the formation of a high-resistance oxide film at the contact surface.

R.B. Richardson, in a paper in a special study group of the AIEE (1957), pointed out that copper-to-copper bus-bar joints were subject to thermal runaway if, at any time during service, a high-resistance oxide film formed at the connection. Silver surfacing of copper joints had been found necessary in many cases to insure operating continuity and minimum maintenance.

Intermetallics could also form, as shown by T.B. McCune et al. (1970), who assessed the effects of heating copper wires coated with tin, silver, and nickel for times up to 200 hours at temperatures of 125°C., 150°C., 175°C., and 200°C. Heating had relatively little effect on the flexibility of silver- and nickel-coated wire but, on the other hand, reduced the flexibility of tin-coated wire by about 30%. In the case of the tin-coated wire, surface layers of oxide-tin-Cu_6Sn_5-Cu_3Sn developed on the copper base and the contact resistance increased. The intermetallics cracked on bending but the cracks did not propagate into the copper wire. Problems with intermetallics were expected to be most severe in smaller gauges of wires.

O.M. Baycura (1969) established the contact resistance for clean copper contacts as a function of load as:

$$R = 99F^{-0.43}$$

R = resistance
F = contact load

P.E. Lawler and L.N. McKenna (1970) found that a light coating of tin on copper would form a copper-tin alloy in a four- to six-month period, and this could affect wire solderability adversely. If a thick tin coating was plated on the copper wire before the draw, the final copper-tin alloy could form on standing.

b.   *Aluminum Conductors.* The first-known use of aluminum as an electric conductor was a telephone line in the stockyards in Chicago, Illinois. This line was installed in 1897, just 11 years after the Hall/Héroult electrolytic process for recovering aluminum had been discovered. In 1898 the first aluminum overhead line was erected in the United States. Today aluminum is used for most overhead lines throughout the world.

N.T. Bond (1975) pointed out that aluminum conductors have given more than 50 years of satisfactory service in power transmission and distribution. Typically, aluminum is used as an electric conductor for more than 95% of the distance from power plant to the user. In Germany, a governmental regulation in 1934 made aluminum cable mandatory for power cables, motors, and coils for domestic use. From 1938 to 1942, Italy decreed adoption of aluminum for all conductors except small, flexible cables and certain types of power cables. The French have used Almélec cables — containing 0.7% magnesium, 0.5% silicon, and less than 0.3% iron — since 1927. Up to 1947, the only serious problem reported was corrosion of the aluminum in ACSR cables. The steel core had been zinc-plated and it is thought that chloride flux, which remained after galvanizing, caused the corrosion. In Great Britain, many Area Boards are now adopting aluminum for 1.1-kV and 11-kV distribution systems. British Specification 2627: 1961 stipulated that insulated cable conductors be manufactured from wire in the 3/4-hard or hard condition.

R.C. Graham (1970) summarized the use of aluminum cable for underground power transmission in Europe, which began in the early 1900's and, by 1946, reached from 30% to 90% usage in England, France, Germany, Austria, and Italy.

From 1946 to 1970, there was extensive use of aluminum cables throughout all parts of the United States, but some utilities were still concerned about corrosion failures at joints. Compression jointing and welding made satisfactory connections, and soldering and bolting were also used to join cables. New York City's first aluminum underground cable was installed in 1952.

J.P. Hayward (1952) reported experiences with aluminum-to-copper connectors used for power-transmission distribution in the Atlantic City region of the United States. ACSR transmission conductors had been in service for 20 years without any connector troubles; all connectors were of the compression type treated with red lead. For 15 to 16 years, the experience with aluminum conductors for distribution had also been satisfactory, except for copper connections located within spray range of salt water. Here the use of aluminum for conductors had been discontinued because connectors failed within six to 12 months. Aluminum service-drop wires had been used since 1944 and only in salt-spray areas had there been problems. In the past no corrosion-inhibiting grease and no taping had been used in joining aluminum to copper conductors, but both grease and taping, along with compression-type connectors, were now being adopted.

C.E. Baugh (1952a) reported that in the San Francisco Bay area, where there have been aluminum transmission lines since 1902, corrosion was the major problem for aluminum conductors in overhead lines. He further concluded that:
1. Aluminum in a bi-metallic couple generally corroded in an acid, alkali, or neutral electrolyte.
2. Spring loading was very often necessary to accommodate cold flow of the aluminum in connectors.
3. The aluminum surface must be properly prepared and a no-oxide grease must be used before jointing.
4. Aluminum-copper joints must be sealed against moisture.
5. There should be a co-ordinated study of aluminum-connection problems.

H.E. Green (1973) wrote on the long-term future necessity of utilizing aluminum conductors. He stated that

> Experience with lines and cables has demonstrated that aluminium can be used with confidence for equipment which is installed and maintained within the electrical industry, where its special problems are fully appreciated.
>   For equipment installed outside the electrical industry, however, caution must be exercised. It has, for instance, been shown that pure aluminium cannot be safely used in wiring in buildings on account of the oxide layer and the tendency to creep when under stress. To integrate an aluminium wire or cable into an electrical system, the oxide film must be displaced permanently from the surface where a joint is made. Plating is one way of doing this.

R.L. Sandstedt and R.B. West (1976) reported that the Corporate Engineering Department of Monsanto Chemical Company specified aluminum for 99% of AWG-2 and larger sizes of 600-volt cables installed during 1973-74. Aluminum cables were first installed in 1965 but the planned use of aluminum cable began only in 1970. By 1975 only three failures of aluminum terminations had occurred. Because of the engineering time spent on proper system design for aluminum, the record of service continuity is better for insulated aluminum conductors than for copper conduc-

tors. As a result of very extensive experience (Monsanto supervised 4,000 connections in 1974), the Engineering Department concluded that the termination is the most critical item when aluminum conductors are used.

F.R. Collins et al. (1970), of the Aluminum Company of America (Alcoa), indicated that EC-6201 and EC-5005 high-strength alloys used for overhead transmission lines did not have the conductivity, strength, bendability, and connection stability required in building wire, that most connectors for aluminum were bulkier and more expensive than comparable devices for copper wire, and that installation involving aluminum required special tools and was more time-consuming.

In the United States there was no significant production of small sizes of aluminum cables until 1946 when an aluminum producer installed them in a major plant extension.

E.W. Perry, Jr. and H.B. Gibson (1972) estimated that of all building wire used in the United States in the following two to three years, one third would be made of aluminum. They gave the 1960 and 1969 usages of copper and aluminum conductors, as shown in Table 1.

Table 1

COPPER AND ALUMINUM CONDUCTOR USAGE

Year	Conductor	Number of Pounds Used
1960	Copper Aluminum	962,000,000 60,000,000
1969	Copper Aluminum	1,684,000,000 253,000,000

Commission's note: 1. Since 1 pound of aluminum is equivalent electrically to 2 pounds of copper, the aluminum used in 1960 amounted to 11% of the total; in 1969, to 23%. 2. The data shown in this table are reproduced, in a different format, from the original table.

2.5.2 Aluminum or Copper Conductors?

Aluminum is being considered more and more for use as a substitute for copper because of considerations that normally govern the replacement of any material:
1. Suitability with respect to specific properties.
2. Availability and stability of supply.
3. Economics or cost.

Table 2 lists some of the important physical and mechanical properties of various grades of aluminum and copper metal that can affect substitution.

The following specific factors must be considered when substituting aluminum for copper.

a.   Resistivity and Conductivity. The *Aluminum Electrical Conductor Handbook* (1971) indicated that both the strength and the resistivity of aluminum were increased by the addition of various alloying elements. Chromium, titanium, and manganese raised the resistivity markedly; copper, silicon, vanadium, and magnesium increased the resistivity; iron, zinc, and nickel increased the resistivity only slightly. The variations in conductivity of EC aluminum and of the high-strength aluminum alloys 5005 and 6201 — which contain about 3% total solute of specific metals — are shown in Table 3.

Table 2

PROPERTIES OF ALUMINUM AND COPPER

Property	Al 99.996%	Al 99.5% [1]	Al EC-grade (99.45% min) [2]	Cu OFHC [3]	Cu ETP 99.92% [4]
Resistivity $\mu\Omega$. cm.					
Annealed	2.6548	2.759	2.790	1.690	1.7241 to 1.70
Hard-Drawn	–	2.826	2.826	–	1.78
Temperature Coefficient of Resistance per °C.	4.29×10^{-3}	–	4.03×10^{-3}	–	3.93×10^{-3}
Electric Conductivity % IACS					
Annealed	64.94	62 to 63	61.8	102	100 to 101.5
Hard-Drawn	–	61.0	61.0	–	97.0
Thermal Conductivity cgs. 0 to 100°C. (Cal/cm sec. C.)	0.57	0.53	0.53	0.92	0.94
Melting Point °C.	660	658.7		1,081	1,083
Thermal Expansion per °C.	23.9×10^{-6}	23.4×10^{-6}	23×10^{-6}	17×10^{-6}	17×10^{-6}
Ultimate Tensile Strength psi					
Annealed	5,600	12,800	8,500 to 14,000	32,700	30,000 to 36,000
Hard-Drawn	–	27,000	18,000 to 29,000	–	64,900
0.1% Yield Strength psi					
Annealed	2,200	4,300	4,000	6,700	–
Hard-Drawn	–	24,000	22,000	–	–
% Elongation					
Annealed	45 to 65	30 to 45	20	60	30 to 40
Hard-Drawn	–	1.5 to 2.5	1.5 to 2.0	–	1.0
Hardness (BHN)	15	18 to 25	–	42	.
Young's Modulus psi	10×10^6	10×10^6	–	17×10^6	17×10^6
Density at 20°C. (gm/cm³)	2,698	.	2,705	8.94	8.89

(1) The major impurities in aluminum are iron and silicon.

(2) Common impurities in EC-grade aluminum are copper, iron, silicon, and titanium.

(3) OFHC is oxygen-free high-conductivity copper.

(4) ETP copper is electrolytic tough-pitch copper containing, generally, about 0.025% to 0.035% oxygen but this may reach 0.1%. During working the Cu_2O globules are broken down and elongated in the direction of working.

Table 3

PROPERTIES OF VARIOUS ALUMINUM-ALLOY ROUND WIRES

Properties	Aluminum-Wire Designation						
	EC-H19	EC-H16 or H26	EC-H14 or H24	EC-H12 or H22	EC-0	5005-H19	6201-T81
ASTM Specification Temper	B230 hard	B262 ¾ hard	B323 ½ hard	B324 ¼ hard	B324 fully annealed	B396 hard	B398 hard
Ultimate Tensile Strength ksi	23.5 to 29.0	17.0 to 22.0	15.0 to 20.0	12.0 to 17.0	9.0 to 14.0	33.0 to 40.0	46.0 to 48.0
Typical Yield Strength ksi	21.0	15.0	13.0				
Elongation % in 10 in.	1.4 to 2.3					1.3 to 2.2	3.0 min.
Conductivity $^{(a)}$ 20°C. % IACS	61.0 to 61.2	61.0	61.0	61.0	61.0	53.5 to 61.0	53.5 to 61.0

NOTES:
1. Property values vary slightly with wire diameter.
2. EC aluminum is 99.45% pure. There are no limits on the 0.55% solute that may be present.
3. Aluminum alloys 5005 and 6201 each contain about 3% total solute of copper, iron, silicon, manganese, magnesium, and zinc.

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According to ASTM specification B230-72 (American National Standard C7.20 ANSI) for hard-drawn aluminum wire for electric purposes (EC-H19), the maximum allowable resistivity at 20°C. is 0.028264 Ω.mm²/m. on an individual test, with the average for a lot being O.028172 Ω.mm²/m. Equivalent values for resistivity of copper and aluminum are given in Table 4. The volume conductivity as a minimum per-cent IACS at 20°C. is 61% for individual test, and 61.2% average for a lot.

Table 4

EQUIVALENT RESISTIVITY VALUES FOR COPPER AND ALUMINUM CONDUCTORS

| Material | Volume Conductivity at 20°C % IACS | Resistivity Constants at 20°C (68°F) | | | | | |
| | | Volume | | | | Weight | |
		Ω.cmil/ft	Ω.mm²/m	$\mu\Omega$.in	$\mu\Omega$.cm	Ω.lb/mile²	Ω.g/m²
Copper	100	10.371	0.017241	0.67874	1.7241	875.20	0.15328
Aluminum	61.0	17.002	0.028264	1.1128	2.8264	436.24	0.076397
Aluminum	61.2	16.946	0.028172	1.1091	2.8172	434.81	0.076148

The figure 1.724 is the resistance in microhms of a 1 cm length of copper bar 1 cm² in cross-section.

$$R = \frac{\rho l}{A} = 1.724\,\frac{\mu\Omega.cm}{1\ cm^2} \times 1\ cm = 1.724\ \mu\Omega$$

Aluminum wire is to be free from such defects as laps, slivers, nicks, inclusions, and excessive lubricant, all of which are not consistent with good commercial practice. The wire must not fracture when it is looped or coiled, with or without a mandrel, around its own diameter. The ultimate tensile strength and the elongation depend on the wire diameter and vary from 23.5 ksi (160mPa) and 2.2% at 0.260 inch (6.604 mm.) to 29 ksi (200 MPa) and 1.2% at 0.060 inch (1.52 mm.).

Since the distribution and concentration of the solute and of the defects can affect electron scattering, the thermal and mechanical history of a metal can affect its resistivity. Thus heat treatments, which increase crystalline perfection, decrease resistivity. These features were illustrated by R.W. Westerlund's investigation (1974) of the mechanical and physical properties of EC aluminum and of aluminum-iron and aluminum-iron-magnesium alloys. Table 5 shows that the resistivity increases with increased solute and with increased solute in solution, i.e., the continuously fabricated wires as opposed to the conventionally fabricated wires.

The technical data show that, for equivalent conductance, the cross-sectional area of aluminum is 1.64 times the area of copper. This means that in branch circuits, AWG-12 aluminum must be used for AWG-14 copper and AWG-10 aluminum for AWG-12 copper. The diameter of aluminum is 1.27 times the diameter of copper. The weight of aluminum is 0.49 times the weight of copper.

Table 5

PHYSICAL AND MECHANICAL PROPERTIES OF CONVENTIONAL AND CONTINUOUSLY FABRICATED ALUMINUM ALLOYS.

Alloys	Rod Fabrication	Tensile Strength ksi mPa		Yield Strength ksi mPa		Conductivity % IACS	Resistivity ρ $\mu\Omega$.cm
Al-0.20% Fe (EC)	Conventional	31	(214)	27	(186)	62.2	2.77
Al-0.20% Fe (EC)	Continuous	31	(214)	27	(186)	61.6	2.80
Al-0.85% Fe	Conventional	29	(200)	26	(179)	60.7	2.84
Al 0.75% Fe 0.15% Mg	Conventional	42	(290)	35	(242)	58.7	2.94
Al 0.75% Fe 0.15% Mg	Continuous	42	(290)	35	(242)	58.0	2.97

Commission's note: The properties shown in this table are typical for 0.0808-inch (2.05-mm.) H19 wire.

b. *Voltage Drop.* An aluminum conductor two AWG sizes larger than a copper conductor is necessary to give the same voltage drop.

c. *Thermal Conductivity.* Aluminum is not as good a conductor of heat as copper.

d. *Heat Capacity.* The heat capacity of aluminum is 30% less than that of copper.

e. *Coefficient of Expansion.* When heated, aluminum expands more than copper. Expansion and contraction stresses are a function of the coefficient of expansion and the modulus — E_{Al} ~10,000,000 psi, E_{Cu} ~17,000,000 psi — which tends to compensate for the higher expansion coefficient of aluminum.

f. *Ampacity.* Aluminum normally is rated to carry 84% of the current that is carried by a copper conductor of the same size. Aluminum with a high-temperature type of insulation can be equivalent to copper of the same size with a low-temperature (rubber) insulation.

g. *Density.* The density of aluminum is 2.7 gm/cm³ and of copper is 8.9 gm/cm³. Aluminum is lighter than copper; 1 pound of aluminum will do the electric work of 2 pounds of copper.

h. *Ultimate Tensile Strength.* Copper has a higher ultimate tensile strength but is not as strong on a unit-density basis. Annealed copper is stronger than annealed aluminum; therefore, copper conductors can be used in the annealed state and EC-grade aluminum is generally strengthened by cold work. The stress-strain behaviour of EC-grade aluminum in the 0 (annealed), H22 (half-hard), and H19 (full-hard) tempers, and of 0 (annealed) copper is shown in Figure 18. In practice aluminum wire two AWG sizes larger has about the same strength as copper.
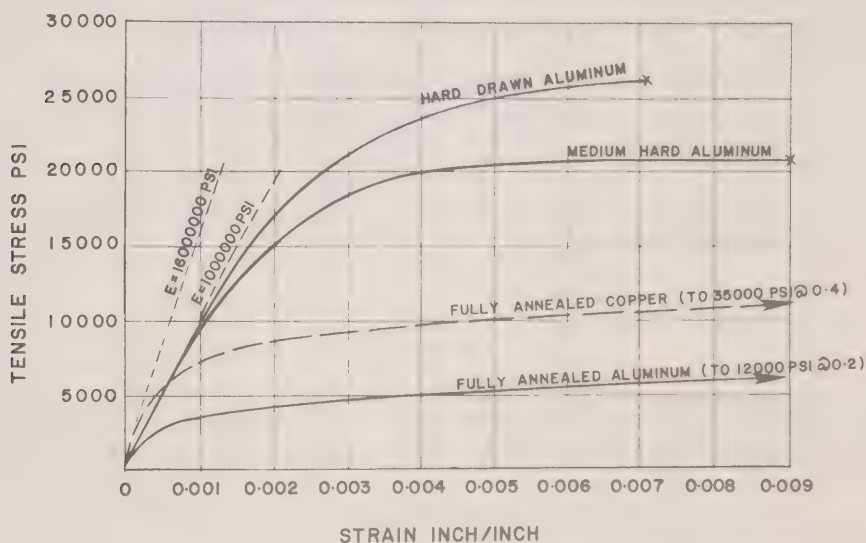
Figure 18. Typical Stress-Strain Curves at Room Temperature (0.081-Inch Diameter Wire)

i. *Ductility.* EC-grade aluminum, regardless of temper, fractures at a strain lower than annealed copper. In Figure 18, the brittle behaviour of the hard-drawn aluminum is shown by the fracture at 0.007 strain, while the increase in ductility in medium-hard aluminum results in fracture at 0.009 strain.

j. *Creep.* Creep behaviour of aluminum and copper as a function of stress and temperature is presented in Figure 19. At room temperature and 18,000 psi, aluminum creeps 100 times faster than copper; a temperature rise from 50°C. to 70°C. causes the creep rate of copper to double and that of aluminum to increase 200 times.

CREEP RATE IN/IN/HR

.1
.01
.001
.0001
.00001
.000001

18000 PSI (AL)

14000 PSI (AL)
25000 PSI (CU)

225000 PSI (CU)
8000 PSI (AL)
20000 PSI (CU)
18000 PSI (CU)
4000 PSI (AL)

TEMPERATURE °F

50   100   150   200   250   300   350   400
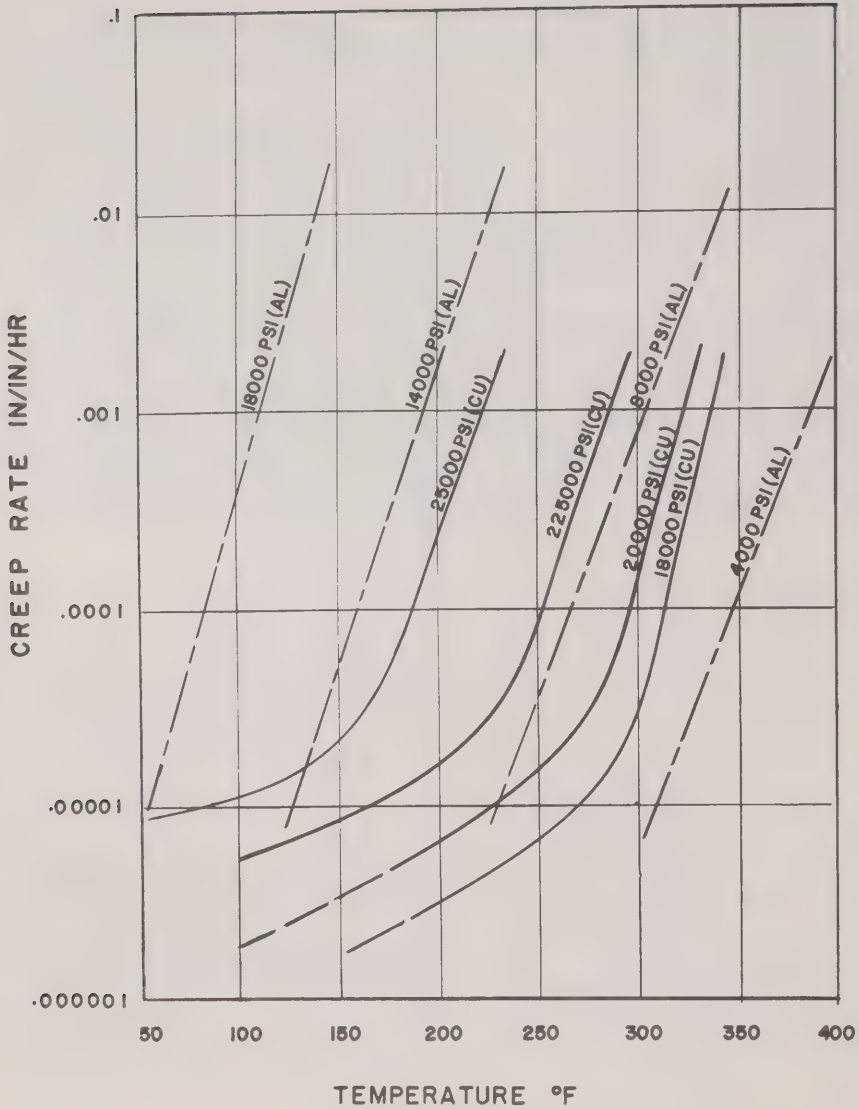
Figure 19.   Creep Rate Versus Temperature at Various Stresses

Annealed electric copper and 99.6% aluminum.

k.   Flexibility. Insulated aluminum conductors have about the same flexibility as annealed-copper conductors two AWG sizes smaller. Ability to flex at the same spot is approximately the same for the same sizes in aluminum and copper. The flexibility can be affected by the type and bonding of the insulation.

l.   Fatigue Strength. For EC-grade aluminum in the H19 temper the fatigue strength is about 7,000 psi, while that for annealed copper is about 10,000 psi.

m.   Corrosion Resistance. Strong alkalis and some acids attack aluminum; otherwise it forms a tight corrosion-resistant film of aluminum oxide (Al_2O_3). Since aluminum is anodic to copper, galvanic corrosion can occur.

n.   Economic Aspects. Aluminum is lower in cost per unit of weight, and sources of supply are stable.

Historically, copper has been the metal used for electric conductors. However, price fluctuations and shortages of this metal — such as occurred during World War II and the Korean War, in the 1950's, and in the mid-1960's — forced the use of substitutes, particularly of aluminum. However, one must always keep in mind the comment by J. St. André (1952) to the effect that the big problem in substituting aluminum for copper is that most electric equipment in use today is designed for connection to copper wire.

In 1966 the cost of conductivity in copper was four times greater than in aluminum. This price differential does not take insulation costs into account.

o.   Connectability. H.H. Watson summarized, in *NEMA Engineering Bulletin 44* (1952), the important problems to be solved before aluminum can be used successfully in branch circuits:
1. Workmen must be retrained.
2. Terminals of wiring devices and low-voltage distribution equipment require redesign.
3. Galvanic corrosion of aluminum-copper connections may be severe. Tin, cadmium, and zinc coatings offer protection against this corrosion.
4. Aluminum is more difficult to join than copper. Welding, soldering, compression, and bolted connections are feasible.

J. Tompkins (1952) reported the results of heat-cycling tests to assess the effect of temper on the *connectability** of bolted, screw, and compression types of fittings to insulated aluminum conductors. He concluded that aluminum fittings minimized differential thermal expansion and, therefore, were best. He also concluded that joint compound appreciably reduced contact resistance on wire and stranded cable, particularly for bolted and screw-type connections and, to a lesser extent, for crimped connections. In bolted connections and in tests of AWG-12 solid-aluminum wire under screw heads in terminal blocks, wires of intermediate temper showed satisfactory results and better connectability than full-hard wires. Wire softer than full-hard with tin-plated copper fittings and bolted connections reduced the effects of differential thermal expansion, spring-back, and a tendency to break at bends. Underwriters' Laboratories, Inc. (UL) have made mandatory the use of intermediate tempers for insulated aluminum conductors in branch-circuit sizes.

2.5.3   Aluminum Conductors for Residential Branch-Circuit Wiring

It is perhaps appropriate to consider some references to the use of aluminum conductors for residential branch-circuit wiring in other countries. It must be borne in mind that in other jurisdictions, especially those outside of North America, the connections, devices, and practices differ from those in Ontario. A chronology of Canadian standards follows, along with some details of the newer aluminum-alloy conductors suitable for use in branch curcuits.

a.   Experience Outside of North America. H.W. Biskeborn (1953) reported that aluminum building wire had been used extensively in Germany since 1934, in Austria and Italy since 1939, and in France since 1940. The European wire had always been 3/4 hard-temper because ductility had been recognized as a prime requisite for long-lasting connections. Bendability of semi-annealed aluminum in AWG-12 is about the same as soft copper while that of hard-drawn aluminum and hard-drawn copper is similar. The European wire-and-device manufacturers had a complete range of fittings that solved all connection problems.

An Introduction to Aluminium Cables, published by Alcan Industries Limited in 1965, stated (p. 17) that solid-core residential wiring cable was "not yet covered by I.E.E. Wiring Regulations, but the aluminium industry is compiling information to prove that small wiring cables in aluminium are reliable, and it is hoped that future revisions of the Wiring Regulations will list aluminium as a standard material."

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* In this sense, *connectability* means the ability to withstand repeated heat-cycling tests without a large increase in contact resistance and a correspondingly large increase in temperature.

In January 1971, the Electrical Research Association in England published a report, *The Possible Use of Aluminium for House Wiring*. The report cautioned that the laboratory tests carried out were not extensive and not severe enough to simulate service conditions, and that because the type of testing was not standardized, interpretation of the results was difficult. In particular, very lengthy testing would be necessary to obtain reliable results because faults still developed after 2,000 to 3,000 hours of current flow. Tests were done on 1- and 1.5-mm² aluminum conductors for lighting circuits fused at 5 amperes, and on 4-mm² aluminum conductors (in place of 2.5-mm² copper) in ring main circuits. Most connectors used were a simple barrel type with a single pinch screw, since no other type of connector tested was better than the barrel type.

The laboratory tests indicated that connections to 1- and 1.5-mm² conductors in lighting circuits fused at 5 amperes performed satisfactorily, but failures occurred on current-cycling connections to 4-mm² aluminum conductors. Multiple connections to 4-mm² aluminum conductors presented problems. Some good connections were made with two 4-mm² wires but three 4-mm² wires could not be connected satisfactorily. Workmanship was stated to be a problem, and the use of torque screwdrivers was suggested as a means of improving connection life. Also, mechanical disturbance after tightening the screws could result in a high connection resistance. Humidity and pollution appeared no more significant for aluminum than for copper and the effects of jointing greases appeared to be minimal. The temper of the wire was not deemed to be a significant variable but half-hard was considered best. No conclusion was reached on the effect of short-time fault currents on terminations.

The report concluded "that aluminium conductor could not safely be recommended for adoption in housewiring without restriction, or substantial derating, so that it would not use the thermal capability of the insulation provided as effectively as does copper." The report also concluded that there was a failure mechanism in aluminum — which was not found in copper-wired connections — which caused a higher incidence of failures in aluminum and which, since the mechanism was unknown, made it difficult to create more reliable aluminum-connector designs.

It was suggested that, in future, consideration be given to the use of crimp-type connections similar to the practice in the U.S.S.R. where aluminum-to-copper crimps were factory-made and aluminum-to-aluminum crimps were made on the job site; to developing suitable fittings for aluminum; to derating aluminum conductors; and to using them only with types of terminals approved for use with aluminum.

The *Electrical Review* (March 3, 1967) reported that the Midlands Electricity Board was wiring a group of about 60 homes in Fosseway Estate, near Moreton-in-Marsh, in the Cotswolds area, with 1.5-mm² aluminum conductors for lighting, 4-mm² aluminum for power sockets and immersion heaters, and 6-mm² aluminum for cookers — all to be PVC-insulated. No results on this experiment have been reported yet.

Wire Industry (May 1971) reported that British Insulated Callender's Cables Limited (BICC Ltd.), Pirelli General Cable Works Ltd., and other United Kingdom manufacturers had conducted tests to assess the suitability of aluminum as an alternative to copper in wiring cables. The poor performance of aluminum when connected to existing designs of accessories was attributed to creep and stress relaxation, and then to oxidation under terminal screws. A number of successful office and home installations in aluminum were made and operated. However, a proportion of failures was experienced through overheating at some socket outlets caused by the number of cables, the formation of the conductor, and the grubscrew torque at the connection.

It was concluded that "with existing accessories, there was an element of risk in the general use of aluminium because in practice some electricians would at some time disregard an essential instruction. There would also be some limitation in the type of conductor which could be used, e.g., whether solid or stranded." Aluminum appeared to be suitable if the oxidation could be controlled and copper-clad aluminum was considered acceptable.

R.C. Milner (1972) reported that experience with aluminum conductors in India was satisfactory at low loads. He also reported that these conductors have been used fairly extensively in the U.S.S.R. without reported trouble; there, however, copper ferrules were welded onto the aluminum at all terminations. In the United Kingdom, the Building Research Station, cable manufacturers, and some electricity boards decided to make trial installations of aluminum side by side with copper.

Analysis of the results of these comprehensive investigations showed that whilst under certain conditions, aluminium conductors behaved satisfactorily, in general their performance was decidedly inferior to copper. Overheating at terminations, a frequent source of failure, was traceable to creep of aluminium under the grub screw of the terminal, leading to inadequate contact. Under such conditions, the resistance of the aluminium oxide caused overheating, expansion of the conductors, further creep and, under the influence of repeated load cycles, eventual failure. The use of torque screwdrivers for tightening grub screws and also re-tightening some time after installation was found to reduce the incidence of failures. However, the results, whatever precautions were taken were by no means predictable. It appeared that only the use of special fittings designed to produce adequate and continuous contact at terminations could ensure aluminium being used with the same confidence as copper. The prospect of manufacturing an additional range of accessories for aluminium did not, understandably, appeal to the manufacturers, and it seemed that the possibility of any large-scale substitution of aluminium for copper in wiring cables was as far away as ever.

M. Dey and P.K. Bhowmick — at the Seminar on Uses of Copper and Aluminum in Electrical Installations, held in Bombay, September 1977 — reported that the Government of India, faced with a copper shortage in about 1963, specified cables with single-wire conductors of annealed aluminum for branch circuits. Failures were reported soon after the introduction of aluminum, and the number increased as time went on. In view of 14 years of unsatisfactory service experience with aluminum conductors in house wiring, the authors recommended consideration of a return to copper conductors in house wiring.

b. *Experience in the United States. Aluminum Building Wire Reference Book* indicates that aluminum power-and-lighting cable has been approved by Underwriters' Laboratories, Inc. since September 1, 1946. The book further states that complete and compatible systems (connectors, switches, wiring, etc.), approved by National Electrical Manufacturers Association and Underwriters' Laboratories, Inc., are available from various manufacturers.

F. Benz reported that at this time (1947), the National Electrical Code in the U.S.A. allowed EC-aluminum conductors to be used for branch circuits with the sizes and ampacities shown in Table 6.

Table 6

RUBBER COVERED ALUMINUM CONDUCTOR DATA

Conductor Size	Conductor Diameter (Inch)	Area (Sq. In.)	Ampere Capacity In Conduit	In Air	Resistance per 1,000 ft. at 25°C. (Ohms)
12	0.081	0.017	17	21	2.68
10	0.102	0.022	25	34	1.68

Commission's notes: 1. The properties shown apply to type RU insulation (160°C.). 2. The data shown in this table are extracted from the original table.

Benz also stated, "in general, aluminum wire may be handled in the same way as copper. This applies to terminals, to connections of aluminum to aluminum and aluminum to copper, and to securing solid aluminum wire under the terminal screws of wiring devices."

W.T. Stuart's conclusions (1952), based on various conferences with development engineers, manufacturers, and contractors, were that satisfactory substitution of aluminum for copper in house wiring was unlikely. In a survey of 70 contractors who had had experience with aluminum, about half reported that they did not believe aluminum was satisfactory for interior wiring systems.

The August 1952 issue of *Architectural Forum* described wiring in Alcoa's 30-storey office building in Pittsburgh, Pennsylvania. "In the beginning, Alcoa's engineers were confronted with the handicap of training electricians to handle aluminum for the first time. Electricians were put through a training program and taught that aluminum differs from copper when used as an electrical conductor." For example, aluminum wires must be one or two AWG sizes larger than the

corresponding copper wires. Aluminum wires up to 4/0 sizes were pressure-connected into compression-type aluminum lugs, which were supplied with joint compound already applied to their hollow interiors. Pressure connections could be made as quickly as soldered joints and remained surprisingly tight and permanent. Wires larger than 4/0 were welded. The article also stated that enormous research was underway to solve soldering difficulties, corrosion, and related joint hardships, and also that electricians throughout the country must be trained in the particular requirements of aluminum wiring.

> Since practically all electrical fixtures are copper wired, Alcoa engineers encountered a problem with bi-metal connections. Thermal expansion of aluminum is greater than copper and repeated cycles of heating and cooling may loosen joints between dissimilar metals. When connecting aluminum wires to copper terminals, Alcoa engineers attach a spring cup washer (cost is about 10¢) which automatically absorbs the uneven expansion. Alcoa engineers stymie electrolytic corrosion here with a fluxlike joint compound, but moisture must be avoided at all costs.

Kaiser Aluminum Electrical Products wired 99 apartments in Ravenswood, West Virginia, with Kaiser aluminum type NM cable (Ka-Flex) in 1957. Kaiser engineers inspected the installation in 1963, after six years of continuous operation, and could find no problems associated with switches, fixtures, or load centres. Scotchlok connectors were used for copper-to-aluminum connections on fixtures. Among other conclusions, the investigators decided that the use of joint compound no longer should be considered mandatory for all aluminum connections.

I.F. Matthysse and S.M. Garte (1970) indicated that EC-grade aluminum wire was not particularly suitable for small (less than AWG-8) wire sizes because it was notch-sensitive and had low creep stress and poor thermal stability. However, several new alloy wires have been developed. The new wires appear to have overcome these problems because they are stronger and more ductile and their mechanical properties remain almost unaffected to 200°C. and for periods of several hours near 275°C.

A chronology of aluminum in branch-circuit wiring in the United States is reported in National Bureau of Standards report *NBSIR* 75-677, December 1974, and in *NEISS News,* Vol. 4, July 1975. The rest of this section has been drawn from these two sources.

Prior to 1966, Underwriters' Laboratories, Inc. recognized aluminum branch-circuit wire for use with any "general use wiring device" except for those using screwless push-in terminals. The EC-grade aluminum alloy in general use could not meet the ultimate-tensile-strength requirement of 15,000 to 22,000 psi in the annealed temper and, therefore, had to be used in the partially annealed or work-hardened temper.

Effective April 1, 1971, UL published the following requirements for aluminum conductors:

Tensile strength: 15,000 psi (minimum)
                     20,000 psi (maximum)
Elongation: 4.5% (minimum)

Effective June 1, 1971, UL specified that aluminum-conductor material meet the following mechanical and thermal test requirements:

Ultimate tensile strength: 15,000 psi (minimum)
Yield strength: 11,000 psi (minimum)
Elongation: 8% (minimum)
Thermal stability: After 4 hours of heating at 200°C., the ultimate and yield strengths should not be less than specified above or not less than 90% of the "as received" strength — whichever is larger.

In the early 1970's, UL proposed that both conductors and devices be subjected to heat-cycling tests. Manufacturers developed new alloys with higher strengths and ductilities, with lower rates of creep and stress relaxation, and with improved thermal stability over previous EC-grade branch-circuit conductors. Details of these results will be given in subsequent sections.

In August 1972, an ad hoc Committee on The Use of Aluminum Conductors with Wiring Devices in Electrical Wiring Systems was organized by UL and the electrical industry. In September 1972, UL revised test specifications for listing aluminum wire and approved the first

wire to meet these specifications. In March 1973, the final recommendations of the Committee were released to the technical press and to various groups associated with the installation of receptacles and snap switches in residences.

c.   Experience in Canada. The relevant standards of the Canadian Standards Association (CSA) permit the use of either copper or aluminum conductors for residential branch-circuit wiring and specify the strength, ductility, and electric resistance of such material. There has been particular concern about overheating at aluminum connections, and the general term *connectability* is used to describe the relative performance of aluminum conductors in high-current heat-cycling tests. The relationship between connectability and physical and mechanical properties is understood only imperfectly at the present time.

Aluminum conductors were first mentioned in the Canadian Electrical Code Part I in 1935 and, on November 28, 1947, *CSA Bulletin 184* first covered the mechanical-property requirements. *CSA Bulletin 655,* issued on October 12, 1966 when the use of aluminum in branch circuits was increasing, stated that the conductors were to be semi-annealed with a tensile strength between 17,000 and 22,000 psi (3/4 hard). *CSA Bulletin 671,* dated March 16, 1967, reduced the tensile-strength range to 15,000 psi to 20,000 psi (half-hard), and introduced a bend test. *CSA Bulletin 671A,* dated May 11, 1977, not only listed the physical and mechanical properties for aluminum-conductor material (ACM) but required that the material pass a high-current heat-cycling test (500 to 1,000 cycles) that used a duplex receptacle with a zinc-plated steel screw.

Alcan has developed an aluminum-alloy conductor material, under the trade name NUAL, which meets these CSA requirements. No data were available on NUAL. However, some information published on other alloys developed to meet the corresponding Underwriters' Laboratories, Inc. requirement for ACM material and some data on the connectability of copper are summarized in 2.5.3 *d.*, which deals with the development of aluminum alloys designed to meet the ACM specification.

On February 3, 1978, the Canadian Standards Association provided a chronological survey of the properties specified since 1936 in CSA standards for conductor materials. This information is given in Table 7.

Table 7

CONDUCTOR-MATERIAL REFERENCES IN CSA STANDARDS

Publication		Conductor Materials
Year	Number	
1936	C22.2 No. 38	Copper
1938	C22.2 No. 48	Copper
1943	C22.2 No. 75	Copper
1947	Bulletin No. 184	Aluminum announced as alternative to copper in Standard Nos. 38 and 75
1948	C22.2 No. 75	Copper
1951	C22.2 No. 38	Copper, or aluminum with content not less than 99.45%
1951	C22.2 No. 48	Copper, or aluminum as covered by Standard No. 38 (1951)
1953	C22.2 No. 75	Copper, or aluminum with content not less than 99.45%
1955	C22.2 No. 38	Copper, or aluminum with content not less than 99.45%
1957	C22.2 No. 75	Copper, or aluminum with content not less than 99.45%
1957	C22.2 No. 48	Copper, or aluminum as covered by Standard Nos. 38 and 75
1960	C22.2 No. 75	Copper, or aluminum with content not less than 99.45%

Publication		Conductor Materials
Year	Number	
1964	C22.2 No. 38	Copper, or aluminum "of the electrical conductor grade"*
1965	C22.2 No. 48	Copper, or aluminum "of the electrical conductor grade"*
1966	C22.2 No. 75	Copper, or aluminum with content not less than 99.45%
1967	Bulletin No. 671	Changes announced in physical properties for aluminum conductors; a flexing test for solid-aluminum conductors (eight 90° bends, i.e., two complete cycles) included
1976	C22.2 No. 48	Copper, or "aluminum alloy 1350"
1977	C22.2 No. 38	Copper, or "aluminum alloy 1350"†
	Bulletin No. 671A	Requirements announced for "aluminum conductor material (ACM)" for AWG-12 and -10 solid conductors, including a high-current heat-cycling test (not required for conduction of aluminum-alloy 1350)

*Electric-conductor (EC) alloy is applied to aluminum material that is at least 99.45% pure aluminum (Aluminum Association's *Electrical Conductor Handbook.)*

†A draft bulletin, which is under consideration by the Wire and Cable Subcommittee, spells out the chemical composition of "aluminum alloy 1350."

Table 8 summarizes the major changes that were made in selected CSA standards beginning with *CSA Bulletin 184,* dated November 28, 1947, and continuing to *CSA Bulletin 1122,* dated May 12, 1977.

Table 8

CHRONOLOGICAL SUMMARY OF MAJOR CSA PUBLICATIONS AFFECTING RESIDENTIAL ALUMINUM-WIRING SYSTEMS

Publication		Summary
Date	Number	
1947 (Nov. 28)	Bulletin No. 184	Aluminum conductors approved as an alternative to copper conductors for use in building wires Minimum size aluminum conductors established as AWG 12 Information provided to guide wire manufacturers until the applicable standards have been revised *Electric Resistivity:* Standard = 17.011 Ω per circular mil ft. at 20°C. Maximum = 17.113 Ω per circular mil ft. at 20°C. *Mechanical Properties:*

Wire Size AWG	Nominal Diameter Inches	Minimum Tensile Strength psi	Minimum % Elongation	
			Before Stranding	After Stranding
14	0.060	27,300	1.3	0.9
12	0.080	25,900	1.5	1.1
10	0.100	24,700	1.5	1.1

Publication		Summary
1951	Specification C22.2 No. 38	Rubber-insulated cables with aluminum conductors required to contain not less than 99.45% aluminum *DC Resistance:* AWG-12: 2.66 Ω per 1,000 ft. at 25°C. AWG-10: 1.67 Ω per 1,000 ft. at 25°C. *Mechanical Properties:* AWG-12: } Tensile strength: 17,000 to 20,000 psi AWG-10: } Elongation (10 in.): not less than 2%

Publication		Summary
Date	Number	
1953	Specification C22.2 No. 75	Thermoplastic-insulated cables with aluminum conductors required to contain not less than 99.45% aluminum *Mechanical Properties:* AWG-12: ⎫ Tensile strength: 19,000 to 23,000 psi AWG-10: ⎭ Elongation (10 in.): not less than 2%
1953	Specification C22.1	Canadian Electrical Code, Part I specified the various sizes of aluminum conductors with different grades of insulation. Previous editions defined the ampacity of aluminum conductors as 84% of that of copper conductors.

Type of Cable	Wire Size AWG	Ampacity	
		Rubber Types R & RW	Thermoplastic Types T & TW
single conductor	12	20	20
	10	35	35
not more than 3 conductors in raceway or cable	12	15	15
	10	25	25

Publication		Summary
1955	Specification C22.2 No. 38	Rubber-insulated cables with aluminum conductors may have semi-annealed or hard-drawn aluminum. *Mechanical Properties:* Solid aluminum conductors smaller than AWG-8 required to have semi-annealed aluminum Tensile strength: 17,000 to 22,000 psi Stranded aluminum conductors may have semi-annealed or hard-drawn aluminum.
1962	Specification C22.1	Canadian Electrical Code, Part I revised ampacity ratings. Temperature classification allotted to different grades of insulation. For AWG-10 single aluminum conductor, rubber-types R & RW, thermoplastic-types T & TW ampacity revised to 30 amperes
1964	Standard C22.2 No. 38	Rubber-insulated cables with aluminum conductors required to use semi-annealed EC-grade aluminum Semi-annealed defined as "three-quarter hard"
1966 (Mar. 29)	Bulletin No. 632	Announced that all insulated wires and cables containing aluminum conductors are required to be identified with the word "Aluminum" or "Alum"
1966 (Oct. 12)	Bulletin No. 655	Wire connectors and equipment intended for use with copper conductors but which may also be used with aluminum conductors required to be marked Cu-Al or equivalent Definition of *equipment* did not include binding-head screws.
1967 (Mar. 16)	Bulletin No. 671	Designations "semi-annealed" and "hard-drawn" eliminated Tensile strength for conductor sizes AWG-14 to AWG-2 solid changed to range from 15,000 to 20,000 psi Minimum elongation requirements deleted Bend test added
1970 (Oct. 8)	Bulletin No. 799	Certification requirements announced for "push-in" receptacles for connection to solid-aluminum conductors Approval for this receptacle withdrawn in 1974
1972	Standard C22.1	Canadian Electrical Code, Part I revised ampacities of AWG-12 and -10 aluminum conductors to be the same regardless of insulation or temperature rating (60°C., 75°C., 90°C.). Rules introduced regarding procedures recommended for terminating aluminum conductors
1974 (Apr. 18)	Bulletin No. 943	Specified requirements to prevent the misuse of aluminum conductors in "push-in" terminals certified for use with only copper conductors. Wiring devices will reject AWG-12 and larger.

Publication		Summary
Date	Number	
1974 (Aug. 21)	Bulletin No. 966	Specified requirements to limit the use of iron or steel terminal screws to grounding terminals only
1974 (Dec. 6)	Bulletin No. 978	Banned use of aluminum wire in recreational vehicles because of potential effects of corrosion and vibration
1975 (Feb. 28)	Bulletin No. 943A	Modification announced to "rejection test" in Bulletin No. 943 (Apr. 18, 1974)
1975 (Apr. 10)	Electrical Notice No. 283	Cartons or reels for non-metallic sheathed cables with aluminum conductors required to be marked "Only for use by or under the direction of a qualified electrician"
1975	Preliminary Standard C22.2 No. 42P	Preliminary requirements announced for receptacles, for use with aluminum conductors, to be marked "CO/ALR" Test specifications made more rigorous with a view to improving reliability of the devices
1975	Standard C22.1	Canadian Electrical Code, Part I modified recommendations for terminating aluminum conductors. Introduced requirement for a 3/4 loop under binding-head screws
1975 (Sept. 15)	Bulletin No. 1027	Banned zinc plating on current-carrying terminal parts of receptacles, attachment plugs, cord connectors, switches, and lamp holders
1975 (Nov. 20)	Bulletin No. 1027A	Supersedes Bulletin No. 1027 (Sept. 15, 1975). Attachment plugs and cord connectors removed from the ban
1976 (Apr. 28)	Bulletin No. 1052	Revisions announced to Standard C22.2 Nos. 55 and 111 regarding adoption of CO/ALR specifications for general-purpose AC switches intended for connection to aluminum branch-circuit conductors
1976 (June 25)	Bulletin No. 943B	Bulletin No. 943A (Feb. 28, 1975) revised to prevent misuse of release slots with all solid conductors AWG-14 and larger
1976 (July 28)	Electrical Notice No. 304	Manufacturers required to submit pigtail-type connectors for retesting if intended for use with flexible copper conductors having more than seven strands. (Previous certification tests involved flexible copper having only seven strands.) Field experience reported a higher-than-normal number of failures for baseboard-heater and other high-current appliance connections using an AWG-12 solid-aluminum conductor and a flexible copper conductor having more than seven strands.
1976	Standard C22.2 No. 48	Non-metallic sheathed cable with aluminum conductors required to use EC aluminum, now called aluminum alloy 1350
1976 (Nov. 15)	Electrical Notice No. 310	Required baseboard heaters having copper leads with more than seven strands to be marked "Not for use with aluminum branch circuit conductors"
1977	Standard C22.2 No. 38	Recognized the change in designation of EC aluminum to aluminum alloy 1350 in thermosetting-insulated cables with aluminum conductors. Bend test added.
1977 (Mar. 16)	Electrical Notice No. 310A	Amended Notice No. 310 (Nov. 15, 1976) Offered marking alternative "Use only with copper branch circuit conductors"
1977 (Apr. 26)	Bulletin No. 655A	Revised Bulletin No. 655 (Oct. 12, 1966) Zinc coatings banned on binding-head type screw terminals for connection to solid-aluminum conductors, AWG-10 and smaller

Publication		Summary
Date	Number	
1977 (May 11)	Bulletin No. 671A	Part A. Specified aluminum-conductor material (ACM) requirements for AWG-12 and -10 solid-aluminum conductors as an alternative to EC aluminum. No composition stated at this time. Part B. Specified requirements for AWG-12 and -10 solid conductors using aluminum-conductor material (ACM). DC Resistance: AWG-12: 2.71 Ω per 1,000 ft. at 25°C. AWG-10: 1.70 Ω per 1,000 ft. at 25°C.
1977 (May 12)	Bulletin No. 1122	Specified test requirements for "special service" wire connectors for use with flexible stranded copper conductors (19 to 41 strands inclusive) to solid conductors (AWG-14 copper; AWG-12 and AWG-10 copper or aluminum)

d.   Recent Developments in Aluminum Alloys for Branch-Circuit Conductors. EC-grade aluminum includes all conducting alloys, not just the EC alloy. As indicated previously, the conductivity and the mechanical properties of aluminum conductors are altered by the type and amount of solute present, by the heat treatment, and by the manufacturing procedures. The properties of some conductor alloys newly developed in various countries of the world have been reported in the technical literature.

In the United States, F.R. Collins et al. (1970) reported the mechanical properties and creep rates of conductors made of EC alloy, aluminum-iron, aluminum-iron-magnesium, aluminum-copper-magnesium, and copper, as shown in Table 9. The table shows that alloy composition, temper, and fabricating procedures can produce wide fluctuations in creep rate, both above and below that of copper. The aluminum-0.40% copper-0.14% magnesium alloy had the lowest creep rate at both 27°C. and 100°C.; even in the annealed state the alloy had a creep rate comparable to copper at 27°C.

Table 9

PROPERTIES OF CONDUCTOR ALLOYS

Alloy	Temper†	Dia. in.	YS ksi	UTS ksi	Elong. % 10 in.	Cond. %	500 Hr 27 C	** Creep-μc 100 C
EC	H19	.149	24.7	28.6	2.0	62.7	630	1190*
	IT	.149	14.3	17.1	13.1	62.2	2230	
Al-.85 Fe	H19	.0822	25.2	28.6	2.3	61.2	2580	
	IT	.0808	17.7	20.0	9.6	61.6	1840	3500*
	0	.0822	9.3	14.8	22.8	62.2	1810*	
Al-.75 Fe-.15 Mg	H19	.0808	32.2	34.0	1.8	59.2	640	1920*
	IT	.0808	19.9	22.5	11.9	61.4	740	1500*
	0	.0808	10.4	19.9	24.5	60.8	4100	
Al-.40 Cu-.14 Mg	H19	.0808	29.4	34.4	2.6	59.0	120	240*
	IT	.0808	13.1	20.5	13.8	60.9	300	380*
	0	.1021	11.5	17.9	11.8	60.6	440	
Copper	0	.0808	28.0	39.8	26.0	100.9	420	

†H19 = hard drawn,   IT = intermediate temper,   0 = full anneal
*5000 psi all others 10,000 psi
**Commission's note: The total extension is shown in micro-inches per inch.

The authors attempted to correlate creep with connectability in duplex receptacles and other wiring devices. To assess the relationship between tensile creep and connectability, AWG-12 solid-aluminum wires were connected to single-backwired, double-backwired, and sidewired duplex receptacles. The backwired receptacles were approved by Underwriters' Laboratories, Inc. for copper but not for aluminum. No joint compound or other surface preparation was used and the screws were torqued to 14 lb-in. Each receptacle was heated 27 times for 2 hours between room temperature and 70°C., followed by 500 current cycles of 15 amperes, then 100 cycles at 20 amperes with on/off times of 15 minutes. Figure 20 illustrates that the increase in contact resistance of EC-grade aluminum at intermediate hardness, and of both aluminum alloys when torqued to 14 lb-in in sidewired receptacles, was less than that of annealed copper.
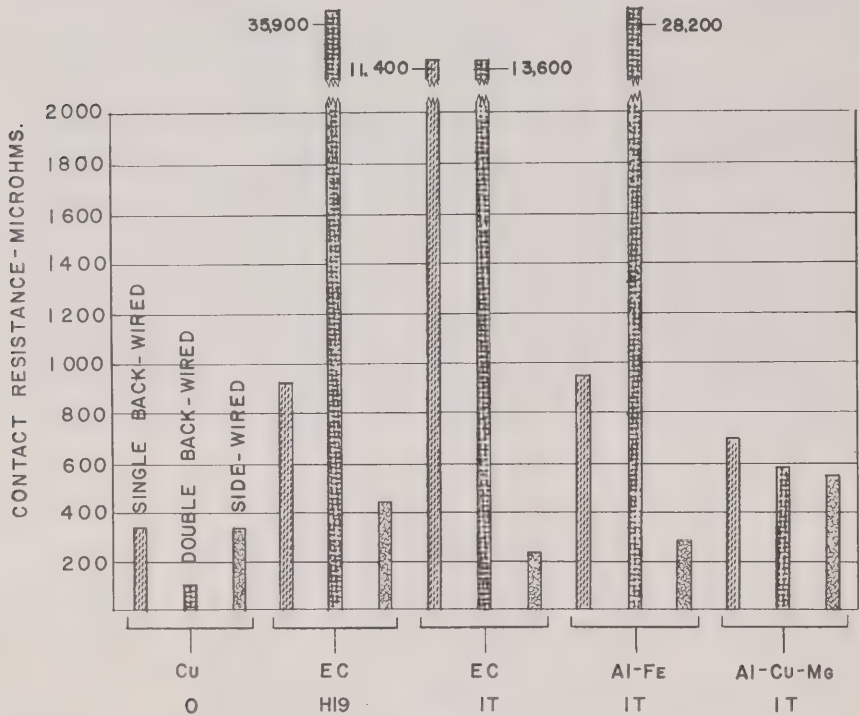
Figure 20. Contact Resistance of Various Alloy Conductors After Heat Cycling in Screw-Pressure Clamp Duplex Receptacles

In only hard-drawn aluminum was the increase in contact resistance slightly greater than in copper. The least increase in contact resistance occurred in the aluminum-copper-magnesium alloy, and this alloy also showed the lowest creep rate. In backwired receptacles, creep is a very important factor. Copper performs best in such receptacles and the aluminum-copper-magnesium alloy is superior to the other aluminum alloys because of its low creep rate.

All conductors were tested in a specially prepared duplex receptacle in which a spring maintained a clamping pressure even when creep occurred. The contact resistances, measured after 143 cycles at 15 amperes with 15-minute on/off periods and then 500 cycles at 45 amperes, are shown in Figure 21. The spring's resilience did not prevent an increase in contact resistance and the measured resistances were generally related to the creep rate of any alloy, i.e., the aluminum-copper-magnesium alloy showed the smallest resistance increase of any of the aluminum alloys and was only 125 microhms greater than that of the copper. The data from these tests confirmed N.T. Bond's previous conclusion that creep caused contact motion which fractures a-spots even at high contact loads.
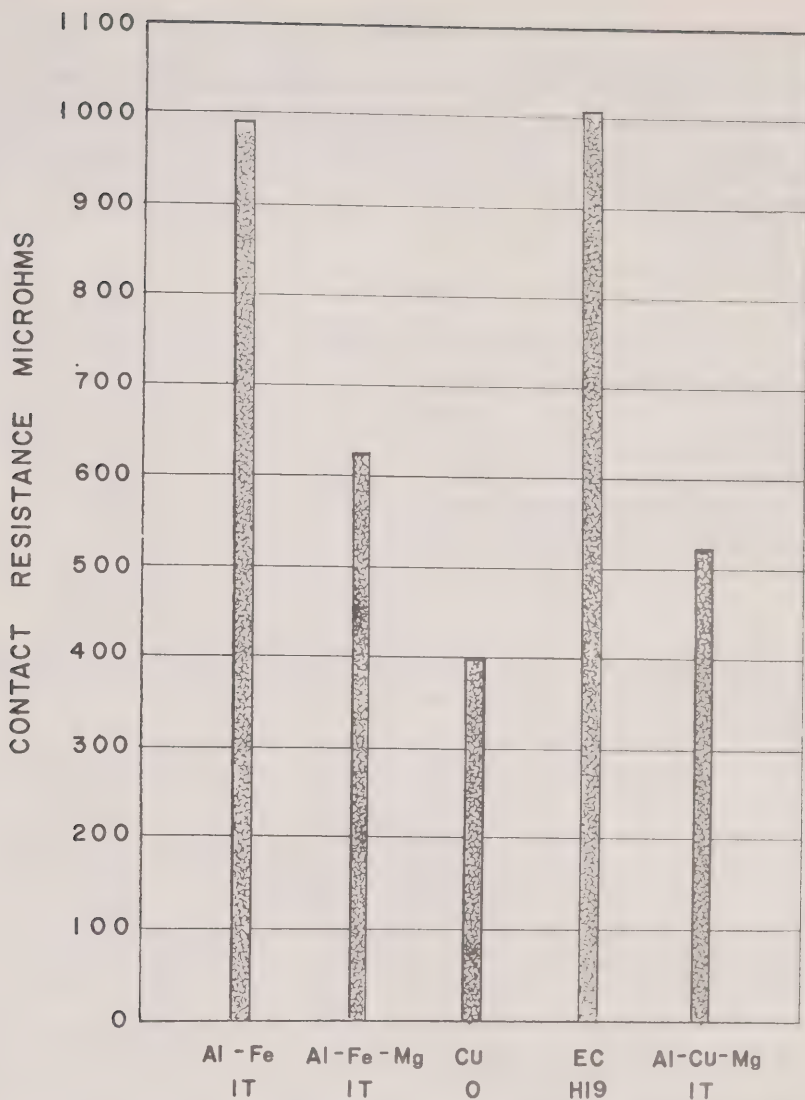
Figure 21. Contact Resistance of Various Alloy Conductors After Heat Cycling in Spring-Grip Duplex Receptacles

Since they offered a significant advance in connectability over EC-grade aluminum, low-creep alloys were tested in a variety of low-cost connectors generally considered to be unsuitable for the EC grade. The ratings listed in Table 10 were established by comparing the level and stability of contact resistance and the temperature rise during cyclic testing. The EC-grade aluminum was certainly worst and the copper undoubtedly best. The aluminum-copper-magnesium and aluminum-iron-magnesium alloys were superior to the aluminum-iron alloy. Table 10 confirms that only copper should be considered for severe service if a twist-on connector is to be used.

Table 10

RATINGS OF NO. 12 AWG SOLID CONDUCTORS IN VARIOUS CONNECTORS

Connector	EC-IT	Al-Cu-Mg	Al-Fe-Mg	Al-Fe	Cu
Duplex recept. large binding screw	A	A	A	A	A/B
Duplex recept. spring grip	D	B	B/C	B	A
Duplex recept. spring grip	D	B	B	D	B
Terminal board screw stirrup, Ni-plated	A	A	A	A	A
Terminal block tubular screw, Cd-plated	B	B	B	B	A
Wire nuts	B	B	B	B/C	A
Wire nuts with 14-stranded Cu fixture wire	C	B	–	–	A
Crimp lug, Sn-plated Cu	C	B	A	A	A

Rating categories:
A, Stable at high currents and sustained temperatures to at least 125°C. . . .
B, Stable at moderate currents and temperatures to about 80°C. . . .
C, Stable through normal excursions of ambient temperature, low currents (communications and control)
D, Unsuitable

In 1971, Super T aluminum alloy was tested in the laboratory by Southwire Company. The comparative strengths of AWG-10 and EC-aluminum conductor wire in the annealed and hard-drawn states are reported in Table 11.

Table 11

PROPERTIES OF EC AND SUPER T
ALUMINUM ALLOYS

Alloy	Temper	Ultimate Tensile Strength psi	Yield Strength psi
EC	Annealed	10,000	4,500
Super T	Annealed	20,000	16,000
EC	Hard-Drawn	28,000	20,000
Super T	Hard-Drawn	36,500	27,500

Southwire developed Triple-E aluminum wire, an aluminum-0.7% iron alloy with high mechanical strength, good thermal stability, and conductivity greater than 61% IACS. Both the improved strength and conductivity were attributed to the precipitation of Al_3Fe, which maintained strength above EC aluminum by inhibiting subgrain growth and conductivity by removing iron from solid solution. The alloy had good thermal stability, and complete recrystallization occurred only above 315°C.

In 1973, Alcoa registered EC Alloy X8076 (formerly designated CK76) with the Aluminum Association. R.R. Westerlund and N.T. Bond (1973) reported the alloy's chemical composition and mechanical properties (shown in Table 12) and indicated that the conductor was suitable for building wire, communication cable, and magnet wire.

They also reported on binding-head screw tests with the alloy and with EC-grade aluminum wires. Thermally unstable connections developed in tests of AWG-12 solid-aluminum conductors of both EC-H24 and X8076-H22 that were connected to a brass strip with a brass-plated steel binding screw: EC aluminum developed a contact resistance of 1,000 $\mu\Omega$ in less than 200 current cycles of 40 amperes with 15-minute on/off periods. The test was stopped after 300 cycles with contact resistance above 3,500 $\mu\Omega$. A smaller increase in resistance (500 to 1,000 $\mu\Omega$) ended the test on the X8076-H22 wire after 400 cycles.

Table 12

PROPERTIES OF ALUMINUM CONDUCTOR ALLOY X8076[1]

Temper	T.S. ksi	Y.S. ksi	% El. in 10 in.	Cond. % IACS	ρ $\mu\Omega.cm$
H19	42	35	1.2	59.5	2.90
H22	20	17	15.0	61.3	2.81
0	16	9	22.0	61.5	2.80

Commission's notes: 1. Alloy X8076 contains 0.6% to 0.9% iron, 0.08% to 0.22% magnesium, and a maximum of 0.10% silicon. 2. The properties shown are typical of 0.808-inch (2.05-mm.) wire. 3. The final column shows the resistivity values. 4. The data shown in this table are extracted from the original table.

It is worth noting that, when the steel screws were replaced with aluminum binding-head screws, a constant low-contact resistance was maintained for 500 current cycles with both X8076 and EC-grade aluminum wires. A severe thermal shock was required to differentiate between the wires. The good connection stability of X8076 was attributed to lower creep and stress relaxation due to magnesium in solid solution and a precipitate of $FeAl_6$. Because the solid solubility of iron in aluminum is ~0.05%, $FeAl_6$ also precipitated in EC-grade aluminum, which contains around 0.20% iron. N.T. Bond and S.A. Wolfe (1973) reported that there was no significant stress relaxation of the X8076-H22 alloy in set-screw terminations but that EC-H19 showed a 33% decrease in torque. Underwriters' Laboratories, Inc. has approved the X8076 alloy in the annealed and half-hard condition (tensile strength, 15,000 to 22,000 psi) for use with connectors approved for aluminum.

Texas Instruments, in the U.S.A., patented a conductor with a copper coating bonded to an aluminum core. Pirelli General Cable Works Ltd., in the United Kingdom, fabricated aluminum conductors of various sizes with a copper coating on 10% of the cross section, and established that no brittle aluminum-copper intermetallics formed during annealing of the composite. The mechanical and physical properties of the wire and its behaviour on heat cycling were also determined. All test results were satisfactory. The breaking strength of 6.5 to 8.5 tons/in² corresponded to the breaking strength of half-hard EC-grade aluminum but the elongation of 15% to 25% was much higher. Heat-cycle tests at 13 and 26 amperes for 11,000 cycles — that is, a 2¹/₂-year period — of 1 hour on/off were satisfactory. Corrosion tests were conducted by nicking the copper coating through to the bare aluminum, then varying the humidity, and spraying with 1% salt solution or with 0.1% sodium hydroxide solution at regular intervals. When the copper cladding was nicked, reversed bending caused the wire to fracture more easily than copper wire.

The ASEA (Allmanna Svenska Elektriska Aktiebolaget, of Sweden) pamphlet AQ14-106E stated,

The most important characteristic of the copper-clad aluminium wire and bar is that they can be connected exactly like solid copper conductors. Connection tests with the most common types of connecting devices, with 2000 temperature rises up to 120°C in the busbar, have not shown any noticeable increase in resistance or temperature at the points of connection. (See Figure 22.)

Figure 23 shows that there is little difference in connection resistance between copper and copper-clad aluminum. The poor connectability of EC-grade aluminum has often been blamed on its low resistance to creep. Since the creep is similar for EC aluminum and copper-clad aluminum, Figures 22 and 23 indicate that the connectability is more influenced by the presence of a layer of copper (and presumably the absence of a layer of Al_2O_3) on the surface of the aluminum conductor.
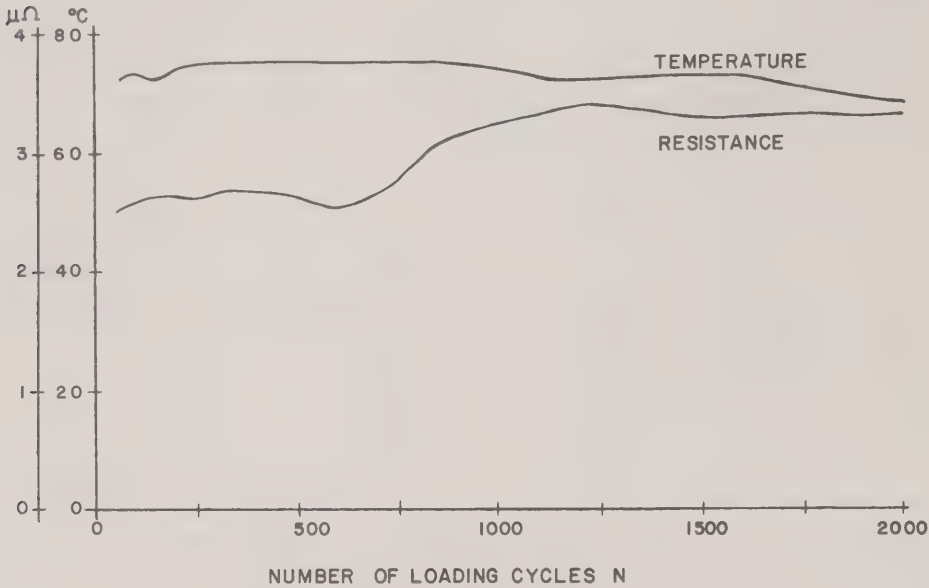
Figure 22.   Temperature and Resistance in a Clamped Connection in Copper-Clad Aluminum Bus Bars as a Function of Temperature Loading Cycles to 120°C.

R. Kumar and M. Singh (1974) reported on the electric-grade aluminum alloy NML-PM2, developed by the National Metallurgical Laboratory of India, which had an IACS conductivity of more than 61%, greater ductility, and improved corrosion resistance over EC-grade aluminum. They suggested that this alloy could be used successfully in house wiring and were arranging for the production of NML-PM2 on a trial basis.

In Sweden, Sieverts Kabelverk AB have developed Sinipal, an aluminum conductor with a 1.5 μ coating of electroplated nickel. *Wire-Coburg* (August 1971) stated that Sieverts found no increase in contact resistance of Sinipal after heating for one year at 200°C.

H.O. Hansson (1970) indicated that aluminum has been considered unsafe for use in house wiring because, in comparison to copper, it has inferior mechanical properties, lower conductivity and corrosion resistance, and poorer contact properties. He reported on current-cycling tests — at 14-ampere current 100 minutes on and 50 minutes off — on 2.5-mm^2 bare-aluminum and Sinipal wires connected to six standard contacts. According to Swedish standards, 14 amperes was chosen as the highest permissible current for a 1.5-mm^2 copper conductor, which corresponds to a 2.5-mm^2 aluminum conductor. There were no failures in Sinipal contacts after more than 10,000 hours of testing, but dangerous overheating occurred in many contacts made with ordinary aluminum wire. Hansson concluded that, for house wiring, Sinipal wiring should be reliable and uncoated aluminum seemed to be unsafe.

In Japan, K. Nakajima and S. Inoue (1970) reported tensile and creep data for MSAL, a new aluminum-alloy conductor, and compared it to copper and EC aluminum. The results are shown in Table 13.

Table 13

PROPERTIES OF MSAL AND EC-GRADE ALUMINUM, AND COPPER

Property	MSAL		EC Al		Cu
	At Room Temp.	At 150 C.	At Room Temp.	At 150 C.	
Tensile Strength kg/mm²	13	10	13	9.5	
0.2% Proof Stress kg/mm²	11	8.5	12	8.5	
Elongation %	17	16	3	7	
Mean Creep Rate %/hr.	1.0×10⁻⁴		3.2×10⁻⁴		0.6×10⁻⁴

Commission's notes: 1. The creep tests were performed on 2.0-mm. wire under a load of 3.2 kg/mm² at 70°C. for a period of one to 200 hours. 2. The data shown in this table are adapted from the original two tables.
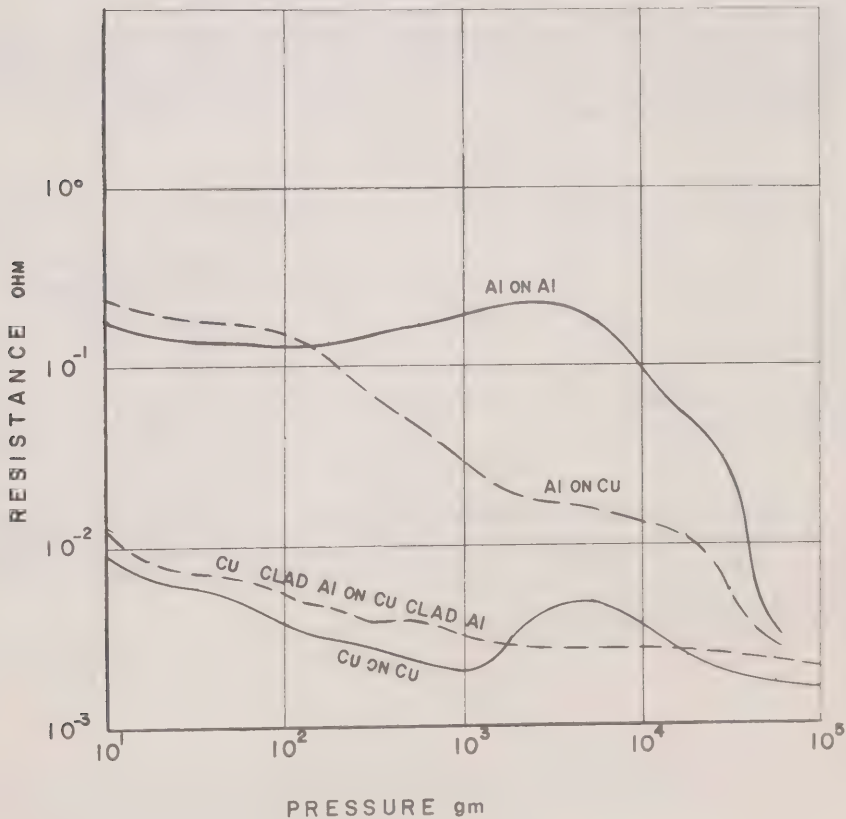
Figure 23. Contact Load Versus Resistance

A high pressure is needed to achieve a good aluminum connection—deformation of the aluminum and fracture of the oxide must occur.

2.5.4 Contact Fundamentals

Electric current (I) flowing through a metallic conductor of uniform cross section is governed by Ohm's law:

$$V = IR \tag{1}$$

$$
\begin{aligned}
V &= \text{voltage, or electromotive force, in volts} \\
I &= \text{current in amperes} \\
R &= \text{resistance in ohms}
\end{aligned}
$$

Also, a current flowing through a conductor with a resistance develops power (P):

$$P = IV = I^2R \tag{2}$$

which heats the conductor. The conductor in turn loses heat to the surroundings. The maximum allowable current-carrying capacity (ampacity) of the conductor is governed by the maximum allowable temperature at which the wire can operate without degradation of its physical, mechanical, and electric properties, or those of the insulation, solder, or metal platings used in the circuit.

Problems arise in any electric circuit when base-metal conductors are joined because metal-to-metal conducting paths (a-spots) must be established by breaking the oxide films that are always present on the surfaces of the conductors. The formation of a-spots can lead to a constriction of the current, as shown in Figure 24.

R. Holm and his wife, E. Holm, developed and published (1967) many of the practical and theoretical studies on electric contacts. They considered that a junction, or connection, added two additional components to the conductor resistance and that the total voltage drop (V_T) measured in the vicinity of the junction was:

$$V_T = I (R_o + R_c + R_f) \tag{3}$$

where

$$
\begin{aligned}
R_o &= \genfrac{}{}{0pt}{}{\text{resistance of conductor}}{\text{over the measured distance}} \\
R_c &= \text{constriction resistance} \\
R_f &= \text{film resistance}
\end{aligned}
$$

The last two terms in equation (3) are often considered separately and have been called the contact voltage (V_c) given by:

$$V_c = I (R_c + R_f) \tag{4}$$

Since the power or heat generated is directly proportional to the resistance and to the voltage drop, and particularly since the heat tends to be concentrated at any location of high resistance, the need for a low-contact resistance to prevent a large temperature rise at the interface can be appreciated.

Holm showed that the constriction resistance for a single a-spot was:

$$R_c = \frac{\varrho_1 + \varrho_2}{4a} \tag{5}$$

where

$$
\begin{aligned}
\varrho_1 \text{ and } \varrho_2 &= \text{resistivities of the conductors} \\
a &= \text{radius of the metal-to-metal contact area}
\end{aligned}
$$
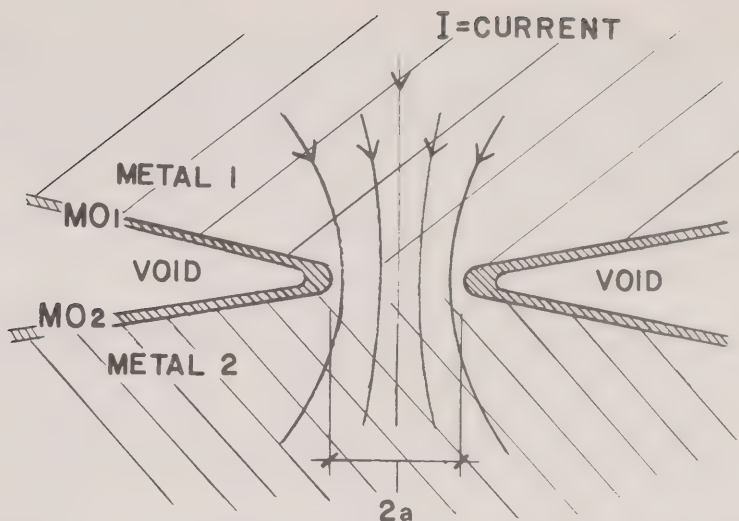
Figure 24.   Schematic Diagram of Constriction of Current at an A-spot or
Region of Metal-1 to Metal-2 Contact

The remainder of the connection consists of voids or contact of
metal oxide MO_1 with metal oxide MO_2.

If the two contacting metals were the same this became:

$$R_c = \frac{\varrho}{2a} \tag{6}$$

and if the resistance of many a-spots of average radius a, acting as parallel conductors, was
considered:

$$R_c = \frac{\varrho}{2na} \tag{7}$$

where

$$n = \text{number of a-spots}$$

The film resistance (R_f) is given by:

$$R_f = \frac{\sigma}{\pi a^2} \tag{8}$$

where

$$\sigma = \text{film resistivity in ohm-cm}^2$$

then the contact resistance for a single a-spot is:

$$R_{contact} = \frac{\varrho}{2a} + \frac{\sigma}{\pi a^2} \tag{9}$$

For a circular constriction in similar metal contacts, Holm developed the following equation to
calculate the increase in the contact temperature over that of the conductor:

$$V_c^2 = 4L \, (T_c^2 - T_o^2) \tag{10}$$

where

$$
\begin{aligned}
L &= \text{Lorentz constant, } 2.4 \times 10^{-8}\left(\frac{V}{K}\right)^2 \\
T_c &= \text{contact-junction temperature} \\
T_o &= \text{conductor temperature} \\
V_c &= \text{voltage drop at contact junction} \\
(T_c - T_o) &= \text{supertemperature}
\end{aligned}
$$

Holm used equation (10) to calculate the voltage at which the metals shown in Table 14 would soften, melt, and boil.

Table 14

SOTENING, MELTING, AND BOILING TEMPERATURES AND VOLTAGES

Material	Softening		Melting		Boiling	
	V_s Volts	T_s °C.	V_m Volts	T_m °C.	V_b Volts	T_b °C.
Al (Aluminum)	0.1	150	0.3	660	–	2447
Cu (Copper)	0.12	190	0.43	1083	0.8	2582
Fe (Iron)	0.21	500	0.6	1539	–	2887
Sn (Tin)	0.07	100	0.13	232	–	2507
Cu-40% Zn (Brass)	.	–	0.2	950	–	–

Commission's note: The values for the materials included in this table are extracted from the original three tables.

Many metals soften at about 0.1 volt and melt in the range of 0.2 to 0.6 volts. If V_c reaches 1 volt and T_o is taken as room temperature, the supertemperature could exceed the boiling point of most metals.

a. *Apparent and True Contact Area.* The *true* area of contact (A_t) of most metals is only a small fraction of the *apparent* area of contact, as shown in Figure 25. If the applied normal load (W) is extremely small, the contacts deform elastically; generally the load (W) acting over the small areas of contact causes plastic deformation and cold welding at some of these junctions. Cold welding is increased if there is a horizontal force as well as a normal force acting on the surfaces. The physical and mechanical properties of the surface layers control the strength of the weld. If σ_y is the yield strength of the softer metal, the true area of contact (A_t) becomes:

$$
A_t = \frac{W}{\sigma_y} \tag{11}
$$
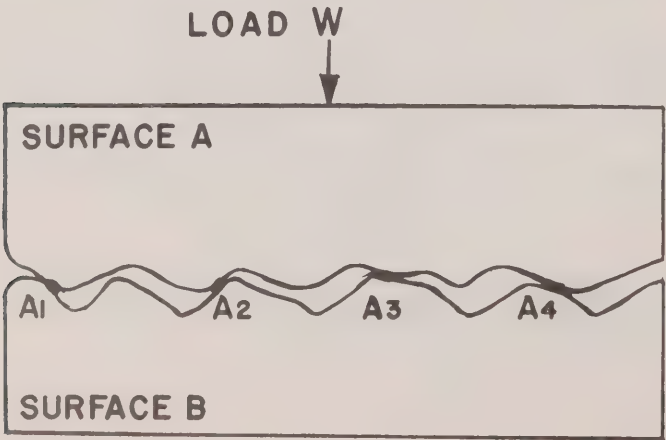
Figure 25. Surface A and Surface B in Contact at Asperities A_1, A_2, A_3 and A_4 Under Load W

Equation (11) has been used to calculate the true area of contact as a per cent of the apparent area of contact at various normal loads. The results are recorded in Table 15. It should be pointed out that the true contact area calculated in this manner includes load-bearing area that is covered with oxide film and is not, therefore, a good electric conductor. Thus the area of metal-to-metal contact — the area of the conducting a-spots — will be much smaller than the calculated values for the true contact area.

Table 15

EFFECT OF NORMAL LOAD ON TRUE AREA OF CONTACT
FOR CLEAN SURFACES

Material	Normal Load W Pounds-Force (Newton)	True Contact Area Per Cent of Apparent Contact Area
Aluminum H19	2.248 (10 N)	0.01
	22.48 (100 N)	0.1
	224.8 (1,000 N)	1.0
Aluminum 0	2.248 (10 N)	0.056
	22.48 (100 N)	0.56
	224.8 (1,000 N)	5.6
Aluminum H19	2.248 (10 N)	0.01
(Iron 0.75%)	22.48 (100 N)	0.1
(Magnesium 0.15%)	224.8 (1,000 N)	1.0
Aluminum 0	2.248 (10 N)	0.02
(Iron 0.75%)	22.48 (100 N)	0.2
(Magnesium 0.15%)	224.8 (1,000 N)	2.0
Copper 0	2.248 (10 N)	0.008
	22.48 (100 N)	0.08
	224.8 (1,000 N)	0.8

Some measurements of true contact area have been made. I.V. Kragelskii (1960) used an optical technique to measure the true area of contact as a function of load for aluminum and copper. His data indicated that, for a given applied pressure between 0 and 10.0 kg/mm², the true area of contact in aluminum is greater than in copper. For example, at 2.5 kg/mm² the true area of contact for aluminum is 9.0% and for copper is 3.0% of the apparent area of contact. E. Rabino-wicz (1965) estimated that for normal loads of 0.1 kg. and higher, the junction diameter varied from 5 μ to 26 μ in copper on copper contacts. J.B.P. Williamson (1968), using microcartography, measured the real area of contact as a per cent of the nominal area of contact for bead-blasted aluminum surfaces with a 40 μ in. C.L.A. finish, as shown in Table 16.

Table 16

CONTACT AREAS BETWEEN ROUGH SURFACES

Nominal Area of Contact Approximate Load /cm² kg	Nominal Area in Contact %
0.2	0.4
0.8	2.2
3.0	7.4
8.0	17.0

R.D. Naybour and T. Farrell (1971) gave the diameters of a-spots in aluminum as 100 to 1,000 nm. (1,000 to 10,000 Å). R.B. Waterhouse (1972) stated that the area of metallic contact was often less than 10^{-7} times the apparent area of contact.

It has been shown that metal surfaces brought together under a normal load can form areas of metal-to-metal contact, which are good electric conductors, and areas of oxides, films, and voids, which conduct poorly or are insulators. Relative motion between the contacting surfaces can destroy the conducting metal-to-metal regions, causing an increase in contact resistance and in contact temperature. Temperature changes can initiate relative motion between two different metals in contact because each will have a different coefficient of thermal expansion. Much of our understanding of the interactions between contacting surfaces comes from studies in the fields of friction and wear and of welding. Rabinowicz estimated that, because the contacting surface asperities were in a state of triaxial stress, the true area of contact was:

$$A_t = \frac{W}{H} \tag{12}$$

where

$$H = \text{the hardness of the metal}$$

This means that the calculated values of the real contact area in Table 16 should be divided by three, since Holm related hardness (H) and yield strength (σ_y) by:

$$H = 3\,\sigma_y \tag{13}$$

By combining equations (7) and (12) and assuming that n circular contacts of radius a are formed, both the number (n) and the average radius of contact (a) can be calculated as:

$$a = \frac{2WR_c}{\pi H \varrho} \tag{14}$$

$$n = \frac{\pi H \varrho^2}{4WR^2} \tag{15}$$

The calculations neglect any surface film resistances and any interaction effects which can occur if the a-spots are very close together. These will increase the constriction resistance and equation (14) will give a low estimate of a. Holm estimated the volume of wear (V) between sliding surfaces as:

$$V = K\frac{W}{H} \tag{16}$$

J.F. Archard (1953) provided a physical meaning for the constant (K) by assuming that welded circular asperities with radius a could form when metal surfaces came in contact, and that hemispherical wear fragments of volume $\pi a^3 (2/3)$ could form when welded asperities ruptured. Then the total wear volume per unit sliding distance was:

$$V = \frac{\pi a^2\, n}{3}$$

where

$$n = \text{total number of welded asperities}$$

The total normal load was supported on an area equal to $\sigma_y \pi a^2 n$ and this meant:

$$V = \frac{W}{3\sigma_y}$$

If only a fraction of the asperity welds produced wear particles, then the wear volume became:

$$V = \frac{KW}{3\sigma_y}$$

where

$$K = \text{probability that a wear fragment is produced at an asperity}$$

This was identical to Holm's expression given in equation (16).

It is possible to express the constriction voltage and temperature in terms of the electric current and the basic physical and mechanical properties of the circuit materials. To formulate a relationship for the temperature rise, the current, the contact load, and the hardness of the materials, equation (16) is modified to account for the change in contact resistance that occurs with change in temperature, i.e.,

$$R_c = \frac{\varrho_o}{2a} [1 + 2/3 \, \alpha \, (T_c - T_o)] \tag{17}$$

$$\varrho_o = \text{resistivity at } T_o$$
$$\alpha = \text{temperature coefficient of resistivity}$$
$$T_c = \text{contact interface temperature}$$

then, equations (6) and (12) are combined to give:

$$R_c = \frac{\varrho}{2} \sqrt{\frac{\pi H}{W}} \tag{18}$$

and

$$I^2 = \frac{16LW}{\pi H \varrho_o^2} \cdot \frac{T_c^2 - T_o^2}{[1 + 2/3 \, \alpha \, (T_c - T_o)]^2} \tag{19}$$

These basic equations show that, for a given current, the contact resistance determines the contact-voltage drop and this in turn controls the contact temperature. As shown by equation (9), the contact resistance itself is dependent on the resistivity of the metal (ϱ) and of the film (σ) and the radius of the metal-to-metal contact a. To minimize contact resistance and supertemperature, it is necessary to minimize both metal and film resistivity and to maximize a. Contact degradation can occur only if the resistivity increases or the area of metal-to-metal contact is reduced. For contact stability, it is necessary to maintain a high value of a throughout the service life of the connector.

b.   Factors Affecting Contact Resistance. It should be emphasized at this point that there is not a complete understanding either of all the factors and the complex interactions that influence the initial formation of a low resistance contact or of the factors that govern the long-term stability or instability of a contact interface. The equations developed so far have shown how the initial area of metal-to-metal contact is related to the contact voltage, current, and resistivity. There are many other factors that affect the initial contact resistance and long-term contact stability. For example, the following factors influence the initial area of contact: surface films (thickness, electric and thermal resistivity and conductivity, friability, hardness, and elastic modulus); surface roughness; applied normal load; applied tangential load; hardness of metal; coefficient of friction of metal and oxide or other surface films; yield strength of metal and oxide; work hardening of metal; ductility of metal; and modulus of elasticity of the metal.

The stability of the contact interface is affected by such factors as current density, operating temperature and time, differential and thermal expansion, vibration, oxidation, galvanic corrosion, stress relaxation, creep, diffusion, thermal conductivity and electric resistivity of surface layer, porosity, intermetallics, emissivity, specific heat, ventilation, conductor material, and cleanness of atmosphere.

The influence of some of these factors in the making and breaking of static electric contacts will be considered in 2.5.4 *c.* to *i.*

c.   Contact Load. Figure 26 illustrates with schematic curves the temperature rise (which is proportional to junction resistance) as a function of clamping force. The curves show that an opti-

mum load or clamping force (O) restricts the temperature rise at the contact interface. The stress in the connection can relax due to elastic spring-back, creep, and stress relaxation. Initially the loss in contact force causes no significant reduction of contact area or rise in resistance or temperature but, if the loss in the clamping force is sufficient, there is an opportunity for a-spots to rupture and oxidize, causing an increase in contact resistance and a rise in junction temperature. When this critical clamping force is reached, a very rapid rise in temperature can occur.
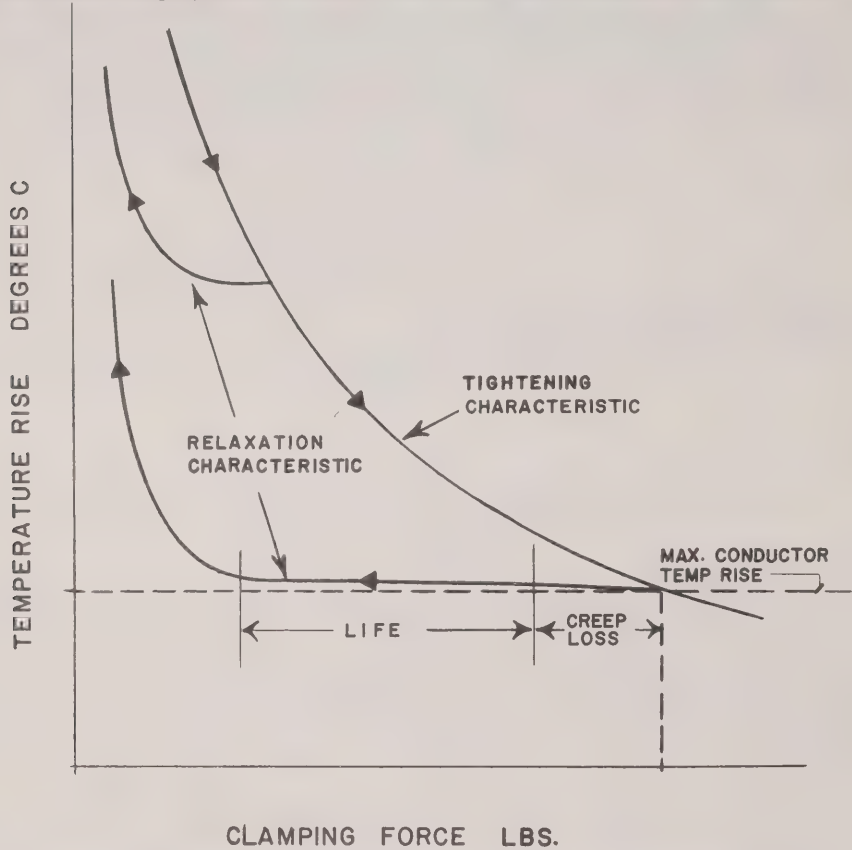
Figure 26.   Schematic Diagram Showing the Relationship Between Clamping, or Contact Force, and Temperature Rise at the Contact Surface

Figure 26 also shows schematically what can occur if less than the optimum load is applied: the contact junction will run hotter than the conductor, and creep and stress relaxation will allow a rapid decrease in clamping force and a rapid temperature rise, as shown in the relaxation (L) curve.

Contact theory has been developed to a stage where the contact resistance-contact force behaviour of aluminum and copper can be estimated from basic material properties, as shown by Holm in Figure 27. The solid lines in this figure represent the resistance values calculated for clean contacts; the dotted lines are the values measured in air.

There is also a great deal of empirical data on the contact resistance-contact pressure behaviour of wires, such as those of J.C. Fan (1971) in Figure 23. This figure shows that a high load can produce a low resistance in both copper and aluminum contacts but a higher pressure is required for aluminum-aluminum or aluminum-copper junctions than for copper on copper or copper-clad aluminum on copper-clad aluminum junctions. Measurement of the constriction resistance in actual connections is extremely difficult and for this reason many researchers assess connector performance by monitoring the junction temperature.
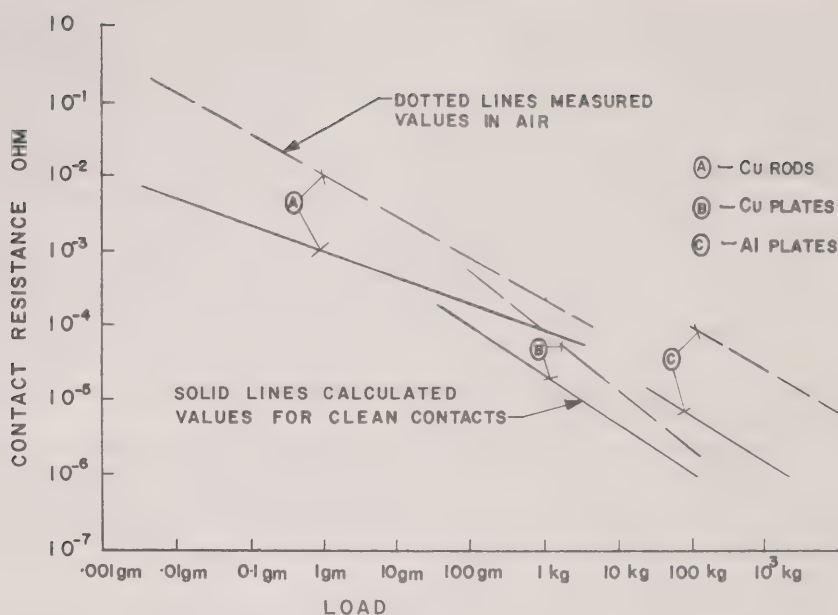
Figure 27. Contact Resistance for Crossed Rods and Plates
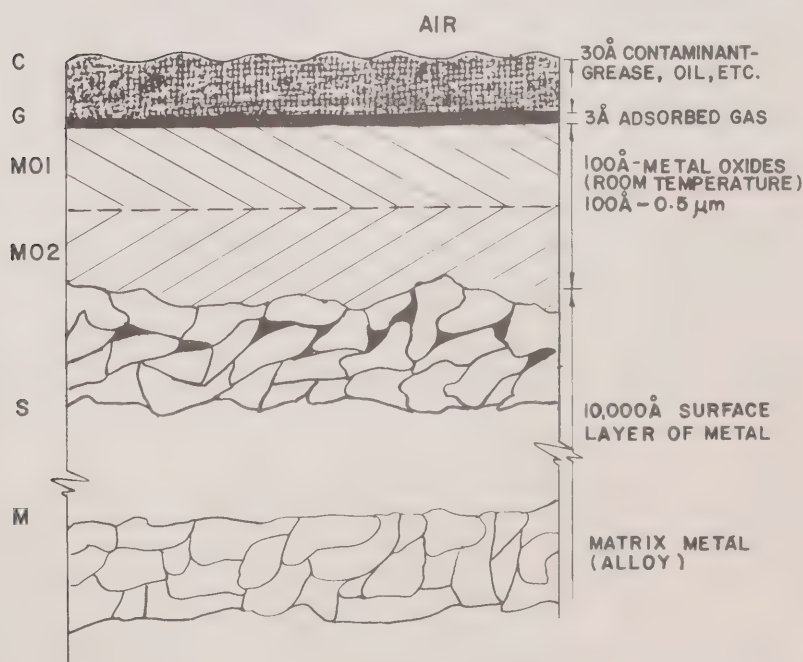
Figure 28. Sketch of Section Through Surface of a Metal

The nature and properties of the contaminating films, adsorbed gases, and oxide films, as well as the structure and depth of the surface layer, can vary with the thermomechanical and chemical history of the metal or alloy.

d. Surface Films. A study of chemistry and surface structure is necessary to appreciate the problems involved in making and maintaining a low-resistance electric contact. Since a metal-to-metal contact is simply a type of weld, it is useful to consider the general requirements for producing a weld between metals. Perfectly flat, clean, metallic surfaces weld on contact because metallic atoms at the surface establish cohesive bonds. By applying both heat and pressure to remove surface films and to establish metallic bonds, a blacksmith welds iron. High pressure alone can rupture and remove surface films and oxides and produce a cold weld in many metals.

The various layers associated with surfaces have been studied and described by a number of investigators. The interpretation of J. Halling (1975) and of D.F. Moore (1975) is illustrated in Figure 28. C.A. Haque (1972) found that carbon, sulphur, and oxygen were the major impurities in the first 100 monolayers of the surface of silver, gold, palladium, and palladium alloys. This means that Figure 28 *should* show surface films of sulphides and oxides or, in some cases, films of elemental carbon and sulphur. Haque also found traces of chlorine on some surfaces; this is of particular interest because of this element's ability to corrode aluminum. Chlorine, which formed when PVC insulation was heated (CPSC minutes of a meeting, dated August 5, 1974), has not yet been shown to be detrimental to electric contacts.

W.E. Campbell (Holm Seminar, 1974, p 282) stated that insulating films could result from such varied causes as the transfer of metal from tools (which sets up galvanic cells); fingerprints; machine oils; electroplate defects; shipping and storage contamination (e.g., cardboard can tarnish silver; vapour from plastic containers can tarnish); installation (e.g., the presence of dust can set up an oxygen-concentration cell); and aqueous corrosion. In the latter case, there should be little problem if the relative humidity is below 50%.

T.E. Graedel (1973) described failures of electric and electronic equipment caused by airborne contaminants, both particulate and gaseous, including sulphur dioxide, oxides of nitrogen, and hydrogen sulphide.

Erratic contact behaviour thus can often be attributed to surface contamination. This contamination is a vital reason for cleaning connectors and conductors before making an electric connection.
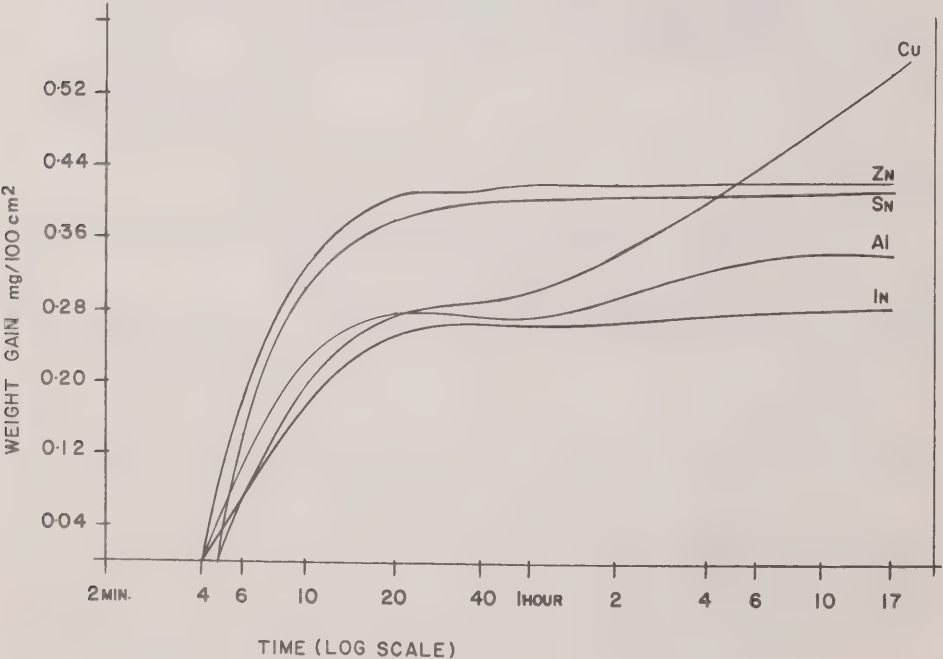
Figure 29.   Oxide Formation on Pure Metals at Room Temperature

e. Oxides. All metals except gold spontaneously form a surface oxide film when exposed to air. R.F. Tylecote et al. (1958) measured the weight gain of several metals after oxidation at room temperature, as shown in Figure 29. The calculated oxide-film thicknesses formed in 2 hours are reported in Table 17.

Table 17

APPARENT FILM THICKNESS ON
COARSE SCRATCH-BRUSHED SURFACES
AFTER TWO HOURS

Metal	Thickness, A
Aluminum	60
Silver	300
Zinc	130
Lead (PbO)	32
Indium	70
Cadmium	26
Tin (SnO)	174
Copper (Cu$_2$O)	175

Commission's note: The data shown in this table have been estimated from test results illustrated in Figure 29. Note that the oxidation of copper did not level off after a period of 17 hours.

M.S. Hunter and P. Fowle (1956) considered that oxide films, whether formed naturally or thermally on aluminum, consisted of a compact layer next to the metal and of an external porous layer. The compact layer was amorphous and grew to a thickness of 10 Å in minutes, and thickened subsequently approximately 10 Å for each 100°C. rise in temperature. The behaviour was the same in moist air, dry air, and oxygen; temperature alone, it appeared, controls oxide thickness on aluminum. Above 450°C. crystalline films of Al$_2$O$_3$ formed and there was an increase of 28 Å for each 100°C. rise in temperature.

R.K. Hart (1956) measured aluminum's rate of oxidation in dry and humid oxygen atmospheres. In dry oxygen at 20°C. the growth was inverse logarithmic and a limiting thickness of 30 Å was reached in several days; in moist oxygen, the growth law was logarithmic for the first 10 hours and then inverse logarithmic, and the oxide film continued to thicken slowly with time. In both cases the films were amorphous.

The evidence reviewed suggests that a 10- to 20-Å film forms very rapidly on the surface of aluminum and that this can grow to 30 to 50 Å in several months in either a dry or a moist atmosphere at room temperature. Thicker films will grow at higher temperatures. Al$_2$O$_3$ adjacent to the metal has an amorphous structure but may be porous and hydrated in regions removed from the metal.

Cuprous oxide (Cu$_2$O) forms in air at temperatures below 200°C., while cupric oxide (CuO) forms at higher temperatures. The Cu$_2$O forms a thicker film than Al$_2$O$_3$ and continues to thicken for many hours. J.C. Mollen and M.J. Trzeciak (1970) showed that the films may be more complex than pure oxide. They described copper samples exposed to industrial atmospheres for periods up to 30 months on which films composed of cuprous oxide (45%), cuprous chloride (45%), and cupric hydroxy chloride (5%) predominated.

W.E. Campbell (Holm Seminar, 1974, p. 282) presented a graph of the effect of seasonal humidity fluctuations on oxidation of enclosed and open nickel specimens. The effect of humidity on increasing the rate of oxidation was evident, as was the beneficial effect of enclosing the specimens. Campbell indicated that mild steels, brasses, and bronzes behaved in the same way (see Figure 30).
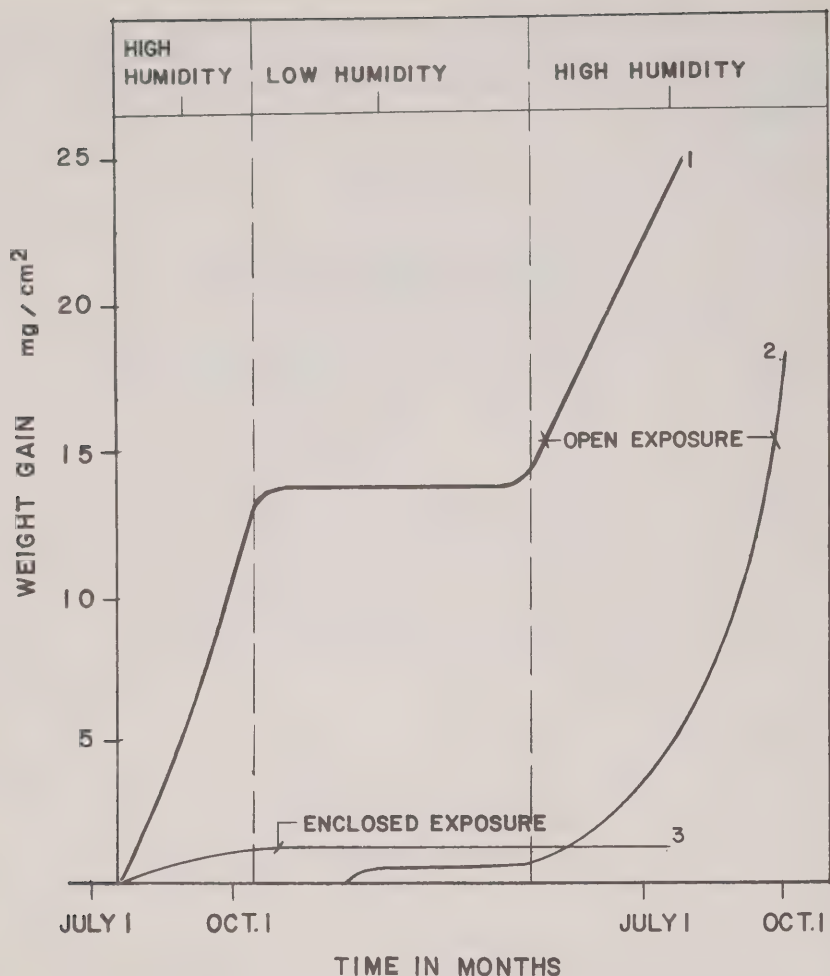
Figure 30.   Effect of Humidity on Oxidation of Nickel

f.   Electric and Mechanical Rupturing of Oxides. Metal oxides may be insulators (Al$_2$O$_3$) or semiconductors (Cu$_2$O) but, in either case, they have a much higher resistance than the metals; for high electric conduction and contact stability, therefore, the oxide must be ruptured and metal-to-metal contact established and maintained. If a thin oxide film is left on a portion of the contact surface, a so-called quasi-metallic surface results and a film resistance component is added to the contact resistance, as shown in Equations (8) and (9). The magnitude of the film resistance for Al$_2$O$_3$ and Cu$_2$O varies with thickness, ranging from 10^6 to 10^7 ohms for Al$_2$O$_3$ and from 0.01 to 0.1 ohms for Cu$_2$O films of 10- to 50-Å thick. It is evident that the contact resistance of aluminum will be high if the oxide film is not removed.

The oxide film may be broken electrically as well as mechanically. If the oxide film is thick (its resistance may be 10^6 ohms), it can be broken down by A-fritting at relatively high voltages. W.E. Campbell (1977) estimated that, for an 840-Å oxide film on copper in contact with gold, semi-conduction would start at ∼0.4 volt and increase as the contact voltage rose to 1.5 volts, when molten metallic junctions could be created. Holm (1967), however, felt that melting was not necessary for A-fritting. The fritting voltage for a 100-Å layer of Cu$_2$O is less than 0.0001 volt, while the fritting voltage for the same thickness of Al$_2$O$_3$ is 40 volts.

New contacts can be formed by A-fritting, while B-fritting, resulting from plastic flow at

a-spots, enlarges the contact area and reduces the constriction resistance. B-fritting can occur when the contact voltage required to cause metal softening (∼0.1 volt) is reached.

There have been many references in the literature to the hardness and tenacity of the Al_2O_3 film and to the difficulty of making a contact through this film as compared to the relative ease of forming metal-to-metal contacts in copper through a Cu_2O film. R.F. Tylecote (1968), however, provided many examples of cold welding of aluminum as well as of copper. Table 18 shows that a lower per-cent deformation is required to initiate welding in aluminum than in copper, and that welding is initiated at a lower deformation in cold-worked metals. It is commonly stated that, because annealed metals have greater ductility, plastic flow occurs more easily through fractures in the oxides of such metals, thus forming larger a-spots. Tylecote considered that, under plane-strain conditions, deformation was more concentrated, and cracks in the oxides were, therefore, larger, in cold-worked aluminum. The significance of Tylecote's work as applied to connector design is apparent.

Table 18

EFFECT OF WORK-HARDENING ON THE DEFORMATION
NEEDED TO INITIATE WELDING

	Hardness H.V.	Deformation %
Al	17.1	28
	25.2	18
	31.9	10
Cu	64	28
	135	12

Commission's notes: 1. Aluminum and copper behave similarly in this welding test. 2. The data shown in this table has been extracted from the original table.

g.　*Normal and Tangential Contact Forces.* The true area of contact caused by a normal load on a clean surface can be calculated by means of equation (11). F.P. Bowden and D. Tabor (1967) estimated the effect of a tangential force on a clean surface, and J. Halling (1975) extended the analysis to include the effects of surface films. Figure 31 shows the beneficial effect of tangential motion (sliding) on the formation of cold welds (i.e., a-spots) and demonstrates that contact areas are not governed by the normal load alone.

N.B. Demkin et al. (1976) concluded that a normal load produced less than 1% area of metal-to-metal contact. When the normal load penetrated the oxide film, tangential motion increased this area 30% to 60% and reduced contact resistance 200 to 250 times for an aluminum-to-aluminum contact, and 100 to 150 times for a copper-to-copper contact. T. Tamai and K. Tsuchiya (1976) also showed that even thick oxide films on copper (∼2,200 Å) could be broken by tangential motion of 0.5 to 1.5 mm. at normal loads of 20 to 100 grams. The original contact-film resistances dropped from 10^4–10^5 Ω to 10^{-2}–10^{-3} Ω after tangential motion; this corresponded to the resistances measured on clean surfaces.

h.　*Surface Roughness and Film Effects.* R.D. Naybour and T. Farrell (1971) measured the contact resistance on crossed rods of soft annealed aluminum (DPH = 20) and hard cold-worked aluminum (DPH = 42). Although soft-soft aluminum combinations produced the largest contact diameters, the hard-soft combinations produced the deepest indentations and also the lowest resistances. These suggested that the relative motion of the surfaces was most important in creating metal-to-metal contacts. Surface roughness was found to affect the initial contact resistance much more than hardness. Figure 32 shows how the contact resistance was affected by load, surface roughness, and abrasion of aluminum just prior to connection.
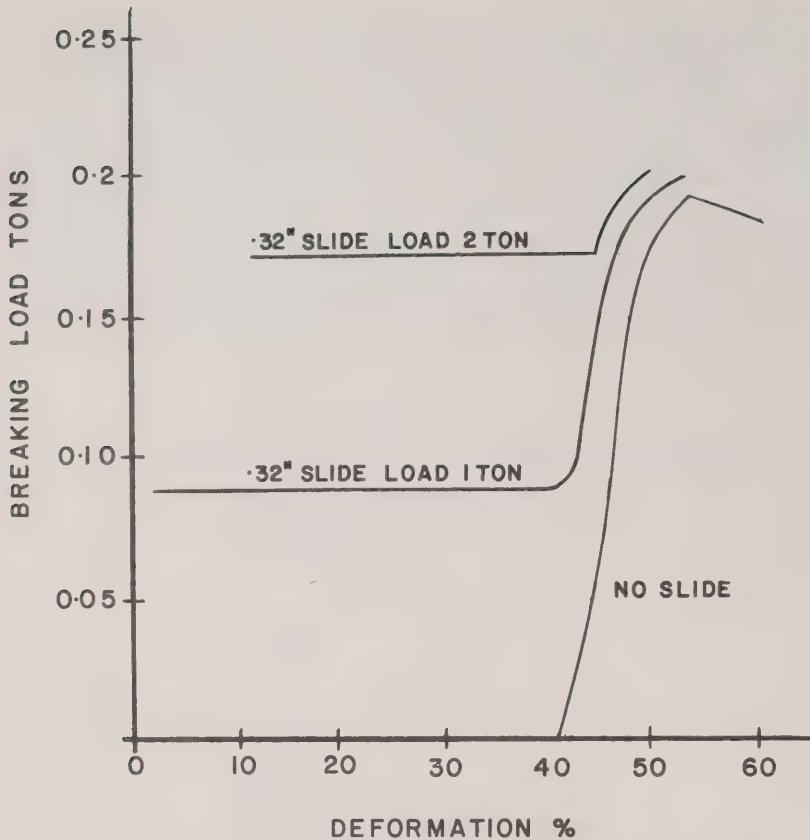
Figure 31. Effect of Load and Sliding on Cold Welding of Aluminum

For annealed samples with smooth surfaces, a load of 2,000 N gave a contact resistance of 4,200 $\mu\Omega$, compared to 20 $\mu\Omega$ for a freshly abraded, rough surface and 90 $\mu\Omega$ for a rough surface abraded 30 days before testing. In unloading the samples with smooth surfaces, an anomalous decrease in contact resistance was observed. This was attributed to shear at the surface when the normal forces decreased sufficiently to allow the release of residual stresses. The contact resistance of smooth aluminum surfaces could be reduced to 10 to 20 $\mu\Omega$ by loading to 5,000 N, which caused about 10% plastic deformation. A load of 2,500 N was sufficient to produce this resistance in a sample with rough surfaces. Since mechanical load cycling in the range of 1,000 to 2,500 N did not increase the rate of contact degradation, the authors concluded that in practice a minimum load of 1,000 N must be maintained at the connection. For these tests the stress was 12.7 N/mm^2.

W.R. Wilson (1955) modified equation (18) by including a surface-roughness term (ΔN) so that

$$R_c = \frac{\varrho}{2}\sqrt{\frac{\pi H}{\Delta NW}} \tag{20}$$

$$\Delta N = \text{a surface topography constant} \sim 10$$

and

$$I^2 = \frac{16LW}{\pi H\varrho_o^2} \Delta N \frac{(T_c^2 - T_o^2)}{[1 + 2/3\, \alpha\, (T_c - T_o)]^2} \tag{21}$$
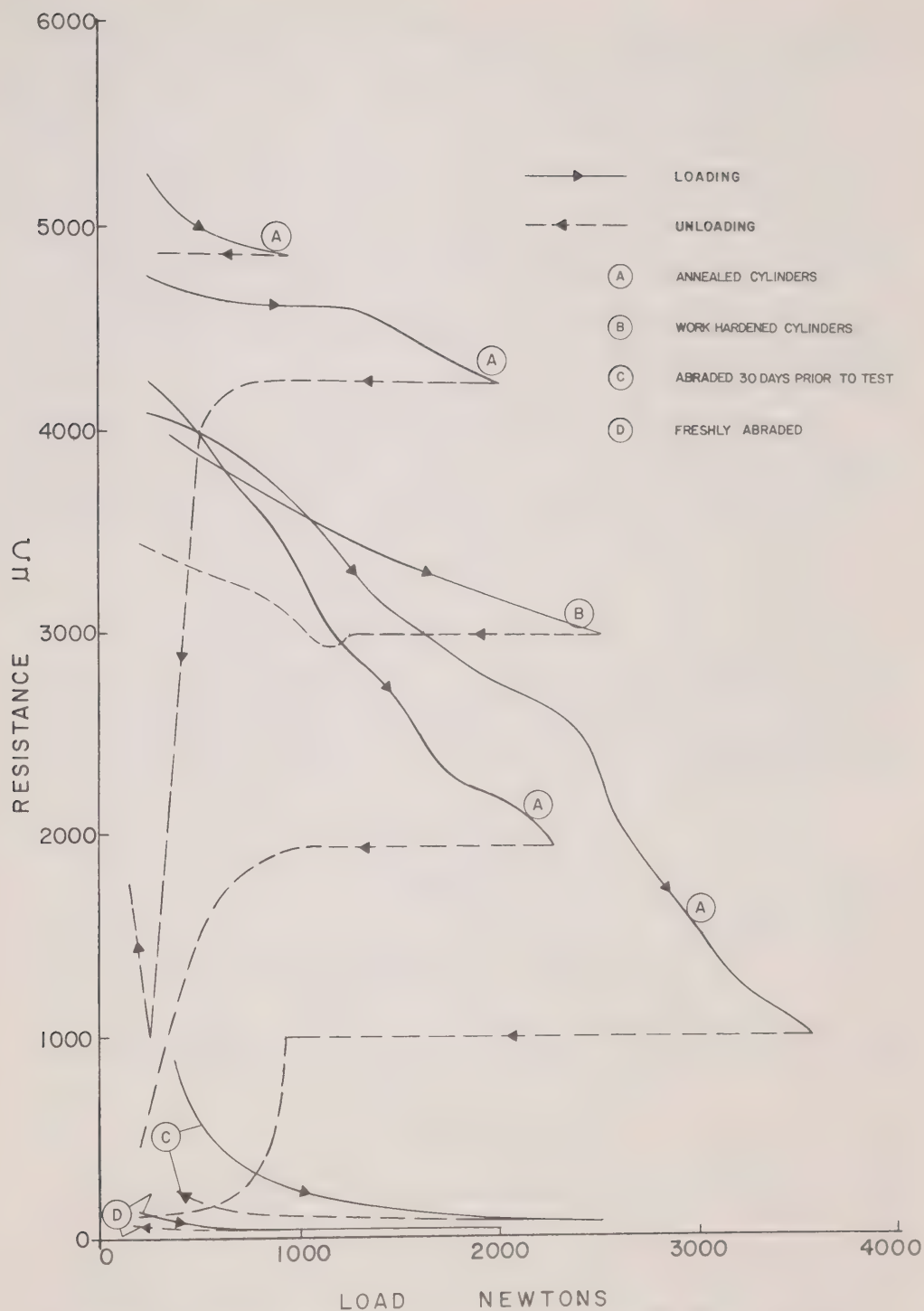
Figure 32. Effect of Normal Loads, Surface Roughness, Surface Preparation, and Cold Work on Contact Resistance

For given physical properties of the contact materials, the contact loads and currents can be related to the contact temperature rise. For example, for aluminum, assuming a temperature rise from 273°K. to 373°K.,

$$I^2 = 1.5 \times 10^4 \, W$$

If W = 0.1 N, R_c = 2.1 mΩ, and I = 38.7 amps.
If W = 1.0 N, R_c = 0.65 mΩ, and I = 122 amps.
If W = 10 N, R_c = 0.21 mΩ, and I = 387 amps.

If a surface-roughness factor (ΔN) of about 10 is used, this simply reduces the force or load necessary to maintain any given temperature increase at a given current by the same amount.

S. Harada and K. Mano (1966) evaluated with some success the effect of surface roughness, hardness, and applied loads of between 0.1 and 100 kg. on the contact resistance of several metals according to equation (22).

$$R_c = \frac{(\varrho_1 + \varrho_2)\sqrt{\pi H} \quad W^{-0.9}}{4L(n/L)_o} \tag{22}$$

where

$$\begin{aligned}
L &= \text{diameter of nominal contact} \\
&\quad \text{surface} \\
W &= \text{applied contact load} \\
H &= \text{hardness} \\
(n/L)_o &= \text{a cutting number (a measure of sur-} \\
&\quad \text{face roughness)}
\end{aligned}$$

At very high loads they found that surface roughness had little effect on contact resistance. Their treatment does not take into account film resistance of the type demonstrated by Al_2O_3.

R.K. Allen (1959) carried out experiments to assess the influence of oxide films on aluminum and copper contacts. He used Holm's estimate of the constriction resistance for elliptical contacts:

$$R_c = \frac{\varrho_1 + \varrho_2}{4a} f(\gamma) \tag{23}$$

where

$$\begin{aligned}
a = (\alpha\beta)^{1/2} &= \text{radius of equivalent circular} \\
&\quad \text{area} \\
f(\gamma) &= \text{factor for elliptical conduct-} \\
&\quad \text{ing area}
\end{aligned}$$

but modified this by including a film-resistance factor (K) that is the ratio of the electrically conducting area to the real area of the contact interface. Then the contact resistance became:

$$R_c = \frac{(\varrho_1 + \varrho_2)\sigma_y^{1/2}f(\gamma)}{2(\pi KW)^{1/2}} \tag{24}$$

Allen then calculated the constriction resistance for a bolted tough-pitch copper joint (20 lb-ft torque) as 1.9 $\mu\Omega/K^{0.5}$ and that for a bolted EC-grade aluminum joint (20 lb-ft torque) as 1.83 $\mu\Omega/K^{0.5}$. However, the corresponding measured values of the joint resistance were 2.09 $\mu\Omega$ for tarnished copper (i.e., only 83.5% of the true contact area was conducting) and 79.3 $\mu\Omega$ for tarnished aluminum, giving a K of 0.000535 (i.e., only 0.05% of the true area of contact in aluminum was conducting). Allen showed that cleaning and polishing both copper and aluminum immediately prior to joining reduced the contact resistance. He also showed that tin plating on aluminum reduced the contact resistance of a flat joint to the range 0 to 0.06 $\mu\Omega$. It should be stressed that a simple normal load alone was not effective in reducing resistance. A tangential

motion with a minimum distance of 0.025 inch and, therefore, a higher torque was necessary to produce this motion.

J.D. Williams and B. Crossland (1976) showed that both chemisorption and adsorption created surface films on metals which prevented welding. Extensive plastic deformation was necessary to clean and weld the surfaces over large areas. Metal surfaces were best prepared for welding by first degreasing and then wire brushing; a reversal of these two steps would result in poor welds. The authors considered that scratch brushing fractured the surface oxide and embedded particles in a rough, cold-worked layer several microns deep. Fractures near asperities in contacting surfaces could coincide, and if the contact pressure were high enough, oxide-free metal could extrude from below the surfaces, meet, and form an a-spot. For appreciable welding to occur, a minimum of 50% deformation would be required; if high-bond strength were required, up to 80% deformation would be necessary.

R.F. Tylecote (1968) believed that scratch brushing facilitated welding by desorbing surface films (particularly moisture), increasing the surface area about three times, and producing a cold-worked surface with embedded oxide particles and a very thin, adherent oxide film. He suggested that scratch brushing was more effective on aluminum, where the oxide is brittle, than on copper where the oxide tends to smear along the surface. In Figure 33 he showed that the welding pressure for 99.5% pure aluminum was ~40,000 psi at room temperature and much lower at higher temperatures, and that a higher welding pressure was required for aluminum of commercial purity (99% to 99.5%) with iron and silicon as the major impurities. The effect of surface chemistry on contact resistance and contact performance has not yet been fully explored.
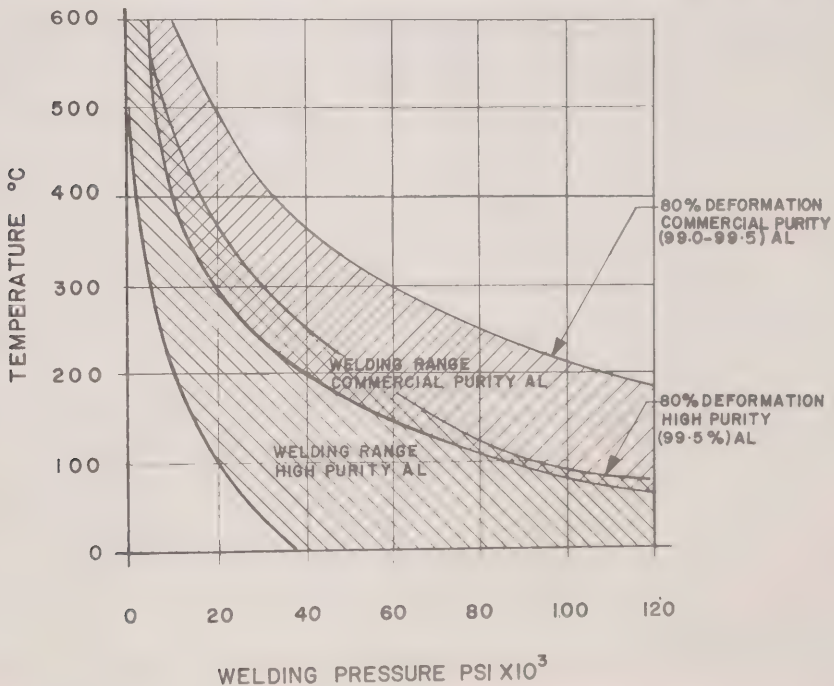
Figure 33.   Welding Conditions for Aluminum (> 99.5%)

i.   *Surface Chemistry.* W.H. Abbott, of Battelle Columbus Laboratories, in a speech at a meeting of the Consumer Product Safety Commission of the United States on August 5, 1974, attributed the unique contact performance of BCL 60, an aluminum-iron-magnesium-copper alloy, to the presence of a magnesium-oxide film. When it was treated to produce an Al_2O_3 film, the conductor performed like any other conductor.

M. Braunovic (1975) showed that in high-purity aluminum (99.999% pure) and an aluminum-0.5 atomic % magnesium alloy, thermal cycling caused impurities to segregate to free surfaces. This strongly affected the hardness, contact resistance, and resistivity. He suggested that vacancies, formed near the coherent metal-oxide interface, diffused into the metal and resulted in a flow of solute from the metal towards the free surface. Auger electron spectroscopy confirmed a higher magnesium content both in the oxide and at the surface in the aluminum-magnesium alloy. The solute segregation to the oxide lowered the contact resistance, but the mechanism is unknown. Braunovic pointed out that many other complex reactions which could affect mechanical and electric properties (e.g., clustering of vacancies, dislocations, polygonization) could occur simultaneously. This area requires much more intensive study.

2.5.5 Connectors for Electric Circuits

a. Contact Testing and Design
(i) Testing in General. For safe and reliable electric connections there must be rupture of oxide films, metal flow, and formation of metal-to-metal contacts large enough — and constriction resistance low enough — that the contact can operate at a low temperature. The connectors must also have sufficient mass to maintain mechanical, chemical, thermal, and electric stability. Mechanical stability is particularly important because a joint will last indefinitely if there is no relative motion at the contact surface. Of particular interest are binding-head screw connections, because of many reported service failures, and compression connectors because it has been suggested they are much more reliable.

C.G. Sorflaten (1960) discussed the design of dual-purpose (Al-Cu) terminals in electric equipment. He pointed out that to establish equivalent conducting paths required a greater clamping force for aluminum than for copper. The increased force can be realized by connector design; for example, increase of the length of the threaded section in a bolted joint, use of a plating for better joint efficiency, and use of a lubricant on the threads to increase the ratio of contact clamping force to torque. In October 1942, *Light Metals* published an article entitled "Junctions in Aluminum Cable," which demonstrated that a 16.92-lb-in torque on a 5-mm. screw pressing on an aluminum conductor — in a screw-sleeve type connector — caused excessive wire deformation when no pad was used between screw and wire. A torque of 8.66 lb-in was recommended for this connection; that of 12.96 lb-in was also satisfactory. In Switzerland a contact pressure of about 2.2 pounds per ampere is required when the current is to pass across one contact area, and about 0.11 pound when the current passes across two or more well-fitting surfaces in a parallel arrangement.

I.F. Matthyse and S.M. Garte (1970) showed that connector life was a function of both current and initial contact resistance. They used an oxidation theory of contact failure to predict that an increase in current from 100 to 2,000 amperes through a 20-$\mu\Omega$ contact could shorten the connector lifetime from 100 years to less than 0.1 year; at constant current, however, an increase in contact resistance from 10 $\mu\Omega$ to 50 $\mu\Omega$ could decrease the connector life from 100 years to less than one year. Actual contacts last longer than the theory predicted because oxide formation levels off and does not uniformly destroy a-spots, as postulated by the theory.

A major problem faced by designers of electric connections is lack of correlation between laboratory tests and service-life expectancy. A brief summary of testing procedures will illustrate the problem.

R.B. Richardson (1957) gave two basic requirements of AIEE and NEMA for an electric connector:

1. The resistance of the connector should be the same or lower than an equivalent length of the conductor to which it is joined.
2. The temperature increase at the connection should be less than the temperature increase of the conductor.

Both these factors are controlled by the joint resistance.

In 1958 Edison Electric Institute, of New York City, published *Tentative Specifications for Connectors for Aluminum Conductors,* which established tentative performance standards for

connectors for aluminum conductors in sizes larger than AWG-6. The proposed testing included the use of:

1. Current cycling for up to 500 cycles with a current sufficient to raise the conductor temperature to 125°C.
2. Monitoring of contact resistance, which must be stable over the last 80% of the test.
3. Monitoring of connector temperature, which must not exceed the conductor temperature.

The tests were designed to aggravate failure mechanisms and were not related to service behaviour.

T. Lemke (1968) discussed the testing techniques that appeared to correlate to service behaviour. A thermal-shock test quickly evaluated the effect of creep, differential thermal expansion, and oxidation on contact resistance. Heat-ageing tests at temperatures above the normal operating temperatures could be used to evaluate the decomposition of insulation as well as any long-term effects that were controlled by diffusion or oxidation. Corrosion testing must take into account the specific product and its operating environment. Vibration testing should be done as well as other mechanical tests that are appropriate for the product and the service conditions.

Current-cycling tests were most important because they approached service conditions more closely than any other test, i.e., the heating was concentrated at the contact interface. They do,
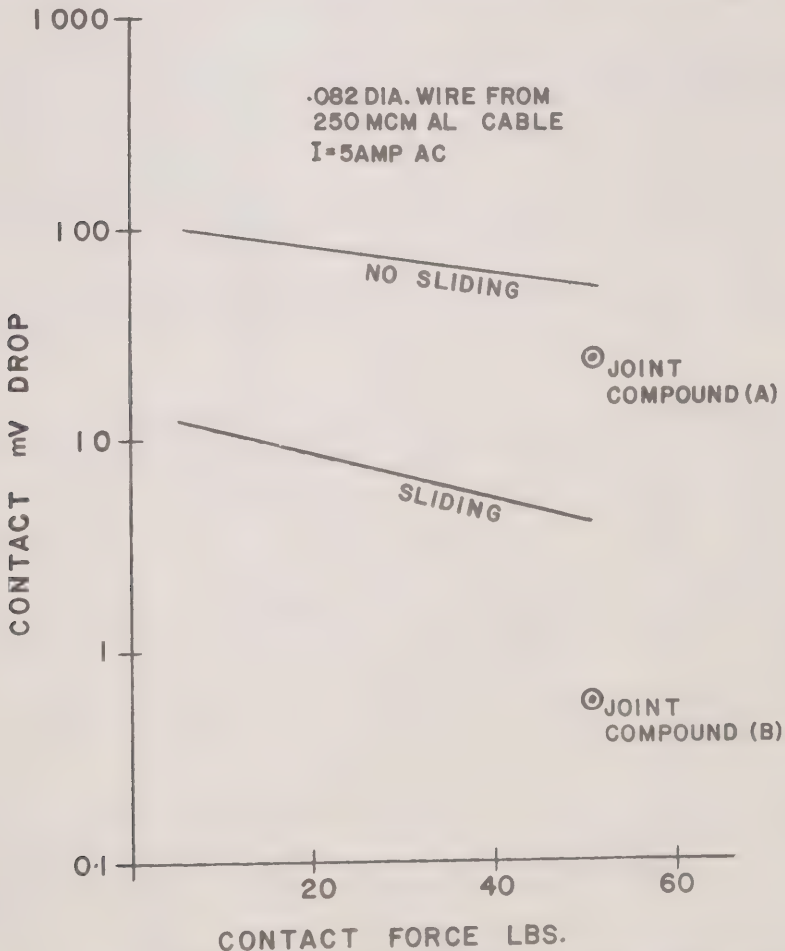
Figure 34.   Crossed-Wire Contact Voltage Drops as a Function of Contact Force

however, take a very long time to conduct. In such tests, a normal requirement is that the connector temperature not exceed the conductor temperature. E.W. Perry, Jr. and H.B. Gibson (1972) indicated that temperature cycling under heavy loads resulted in differential thermal expansion between an aluminum conductor and a copper connector, and in loss of contact force.

(ii)   Testing Aluminum Terminations. N. Shackman and R.W. Thomas (1962) pointed out that "there is general agreement that an aluminum conductor cannot arbitrarily be used with connectors which have been designed primarily for a copper conductor" and that connectors must be designed for specific uses with aluminum conductors. To illustrate features of connector design, they tested copper and aluminum conductors in crossed-wire tests and in set-screw connectors of copper and aluminum alloys. The connectors were tin-plated and the set-screw size,
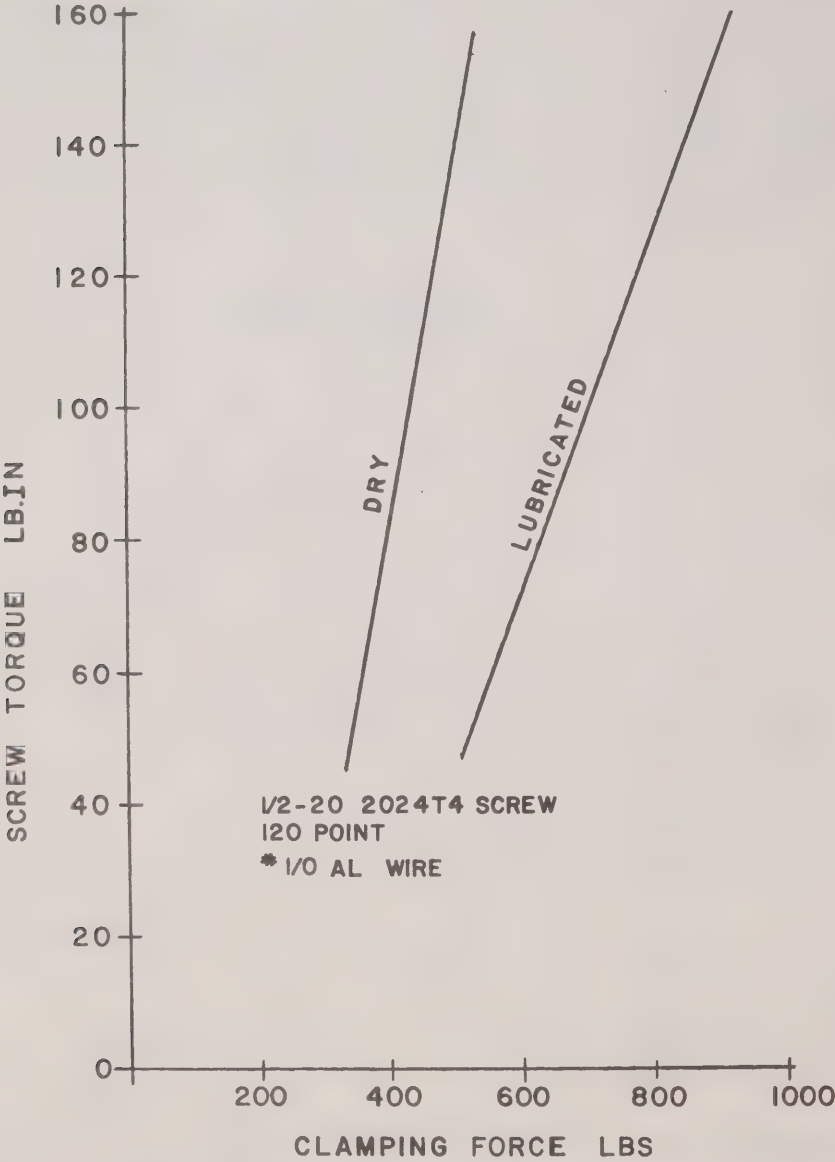
Figure 35.   Screw-Torque Versus Clamping-Force Relationships

shape, and material were varied. Aluminum set screws were superior to those of brass and steel, presumably because they matched the thermal expansion of the aluminum-alloy connector body. Pointed set screws were better than flat set screws because they caused a larger deformation in the conductor. In the crossed-wire tests on aluminum conductors, the authors showed (see Figure 34) that a high-normal clamping force (no sliding) reduced the contact-voltage drop and this effect was enhanced by a tangential force (sliding). The beneficial effect of a joint compound containing metal particles (A) is also shown in Figure 34, as is that of a joint compound (B) which removes the Al_2O_3 film chemically.

A typical torque-force relationship, which is governed by the geometry of the screw as well as the lubrication of the screw threads and point, is shown in Figure 35. The beneficial effect of a lubricant is evident.

The effect of elevated temperature was assessed by heating aluminum-wired connectors for 24 hours at 100°C. Presumably because of creep and stress relaxation, 49% to 60% (average 55%) of the original connector torque was lost.

Current-cycling tests for up to 1,000 cycles, with 1- to 1½-hour on/off periods and with periodic wire disturbances, were used to assess relative connector performance. Failure was assumed to occur when the connector temperature reached 150°C., at which temperature thermal runaway generally occurred. The wire-disturbance test is said to simulate movement of the conductor during wiring, differential thermal expansion, and the effect of the passage of short-circuit currents.

For testing aluminum conductors and devices for branch circuits, Underwriters' Laboratories, Inc. in the United States have developed heat-cycling and CO/ALR tests. These have been adopted in Canada by Canadian Standards Association. In common with earlier tests for the larger sizes of aluminum conductors, these are performance tests for which there is no correlation with service behaviour.

The Electrical Research Association reached an interesting conclusion concerning the number of tests required to establish reliable failure rates. The Association published its conclusions in *The Possible Use of Aluminium for Housewiring* (January 1971):

> From probability theory it has been estimated that to get a 90% chance of measuring failure rates in the region of one per cent, a sample made, tested and assessed uniformly, will need to contain about 300 or more specimens.

Table 19

NOMINAL AND DESIGN CONTACT RESISTANCES FOR ALUMINUM AND COPPER BRANCH-CIRCUIT SIZE WIRES

Diameter		Conductor	Conductivity % IACS	Resistivity μΩ cm.	Resistance (ohm)		
cm	In.				20 φ	10 φ	5 φ
0.2057	0.081	AWG-12 EC-Al	61.0	2.8264	0.000350	0.000175	0.000088
0.2591	0.102	AWG-10 EC-Al	61.2	2.8172	0.000277	0.000138	0.000069
0.1626	0.064	AWG-14 Cu	100.0	1.7241	0.000269	0.000134	0.000067
0.2057	0.081	AWG-12 Cu	100.0	1.7241	0.000214	0.000107	0.000053

N.T. Bond (1973) used contact resistance as a performance index for an electric connection. An ideal contact has $R_c = 0$, and an open circuit has $R_c = \infty$. R_c must be defined in terms of specific voltages and currents since a contact resistance of 500 $\mu\Omega$ could be acceptable at 10 amperes but would cause severe overheating in a 1,000-ampere circuit. Bond and S.A. Wolfe (1973) stated that experience showed that a contact resistance that was equivalent to a 20-diameter length of control conductor was satisfactory for many electric applications. A more conservative and practical limit was a contact-resistance increase equal to that of a 10-diameter length of control conductor. The authors felt that a good design objective was a

contact resistance equivalent to a 5-diameter length of control conductor. This value of contact resistance became the acceptability reference level (ARL) for a specific conductor. For branch-circuit wire sizes in aluminum and copper, this is equivalent to the resistances given in Table 19.

Table 20

ORDER-OF-MERIT SCALE FOR ELECTRIC CONTACTS, PERFORMANCE
WITH TENTATIVE MAXIMUM ACCEPTABLE LIMITS
OF CONTACT RESISTANCE

	Tentative Class Descriptions	Tent. R_c	MAL, % ARL ΔR_c
10	·············· Open Circuit ··············	*	*
9	Failure modes	2000	1000
8	Poor quality	1600	800
7	Control	1200	600
6	Limited service	800	400
5	Design objective for 7th class	400	200
4	Typical applications	200	100
3	Design objective for 5th class	100	50
2	Stringent applications	50	25
1	Design objective for 3rd class	20	10
0	High quality ·······Ideal·······	0	0

(Left axis label: Order-of-Merit Scale of Electric Terminations)

*For interpolation, R_c = 20,000, ΔR_c = 10,000

Table 20 is Bond's order-of-merit scale for electric contacts with tentative contact resistances (R_c) and maximum acceptability limits (MAL) as a per cent of (ARL). If R_c exceeds (MAL) we have a contact failure. In a well-made joint an initial contact resistance well below (MAL) can be established; now there is a problem only if an increase in contact resistance occurs.

(iii) Binding-Head Screw Connections. The maximum acceptability limit that Bond suggested for binding-head screws on solid branch-circuit conductors is 400% (ARL), with the design objective of 200% (ARL). Figure 36 shows these values and the results of heat-cycling tests for AWG-12 H24 aluminum conductors installed at 6 lb-in torque on non-plated brass conducting strips with zinc-plated steel screws and with non-plated aluminum screws and subjected to 500 cycles at 40 amperes for 15-minute on/off periods. The steel screws failed within 300 cycles while the aluminum screws performed satisfactorily. Figure 36 also shows that indium plating of the brass strip reduced the initial contact resistance and maintained the low value for 500 current cycles. These results leave no doubt that design plays a significant role in binding-head screw terminations. W.A. Miller (1969) stated that a binding-head screw was suitable for both aluminum and copper connections. He believed that differential thermal expansion of aluminum and copper was a problem and that this was solved best by using a tin-coated aluminum connector. He warned that the correct compression tool must be employed if aluminum compression lugs were used in branch circuits.

R. Holm (1967) investigated the contact resistance of aluminum and copper wires connected to nickel and zinc clamps by means of terminal screws. The screw pressure (P) was calculated from:

$$P = \frac{2\pi M}{2\pi r\left\{\frac{f_1}{1.1} + 1.1 f_2\right\} + h} \tag{25}$$

P = contact load in newtons
M = the torque in Nm
h = the screw pitch in m
2r = diameter of screw thread in m
f_1 = coefficient of friction in thread
f_2 = coefficient of friction in screw head
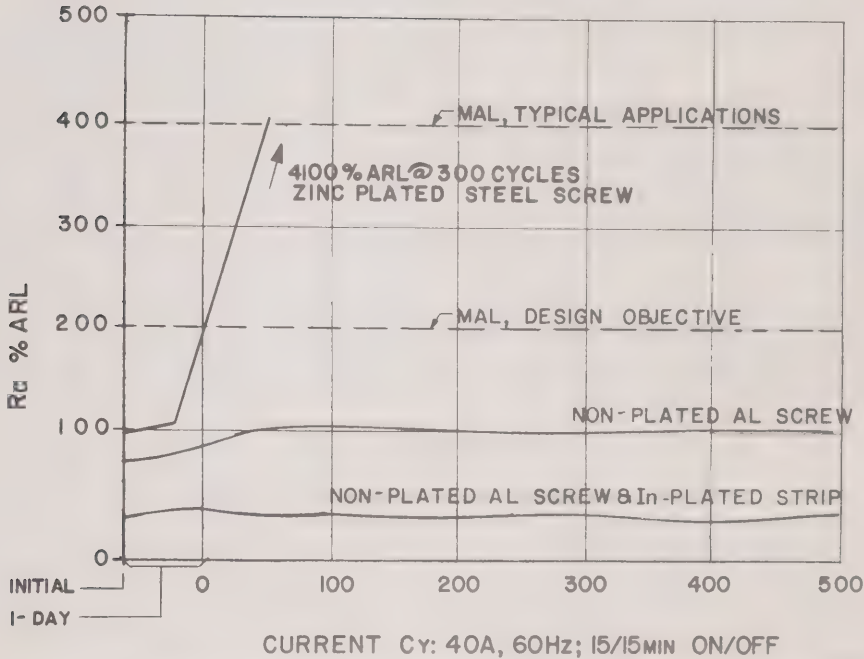
Figure 36. Comparison of Wire-Binding Terminations with Plated-Steel and Non-Plated Aluminum Screws at 6 lb-in on AWG-12 EC-H24 Wire

This equation shows that friction makes the clamping force about ten times smaller than it would be without friction. The pressure can vary with changes in f_1 and f_2; for example, if there is some oil on the screw, f_1 may vary from ~ 0.15 to 0.25. On brass and steel f_2 may reach 0.4, and 0.7 on aluminum and zinc. One CO/ALR device is said to depend on oil on the screw threads to increase contact pressure.

Holm reported the values of initial contact resistance at room temperature and those measured after storing for periods of time up to 12 months at 100°C. (see Table 21). The contacts were tightened after the first month to the original torque without any effect on the contact resistance.

Table 21 demonstrates again the importance of a high-contact load (in this case, pressure P) in establishing and maintaining a low-contact resistance: for wires, loads above 200 N are satisfactory, except in the case of zinc; for flat, clean contacts, Holm said that the contact load must be increased three to ten times to produce a low-contact resistance.

Holm considered that temperature stability of the connections held at 100°C. for a year was extremely good but suggested that temperature cycling would have a greater effect. Further tests showed that a copper contact held at 150°C. with pressure of 350 N experienced a decrease in contact resistance. For aluminum contacts at the same temperature with pressure of

50 N, an increase of resistance of 10% was observed. Holm reported the results of Richter and Schade who in 1920 and 1938 found that screw contacts with aluminum, which were good during the first year, remained fit for use for 20 years more. Twist contacts were found to be unreliable. These results suggested that tightly made aluminum binding-screw connections should have a reasonable life expectancy but that they cannot be expected to perform as well as copper in which actual decreases in contact resistance have been observed over a period of time.

Table 21

CONTACT RESISTANCE OF ALUMINUM WIRES CLAMPED UNDER A
TERMINAL SCREW

Wire and its diameter mm	Clamp ledge	Screw diameter mm	Torque M Nm	P about N	Resistance at room temperature $10^{-4}\Omega$; t in months after clamping			
					t=0	0.5	2	12
Cu 0.5	Ni	2	0.13	280	0.08	0.05	0.05	0.04
Al 0.28	Ni	2	0.057	110	0.27	0.30	0.28	0.13
Al 0.28	Zn	2	0.057	90	0.8	18	400	1600
Al 0.28(1)	Zn	2	0.207	280	1.0	4.5	18	23
Al 0.28	Zn	2	0.207	320	1.7	3.2	0.84	0.83
Al 0.06(1)	Ni	4	0.207	130	0.43	0.48	0.50	0.58
Al 0.06	Ni	4	0.407	250	0.09	0.09	0.08	0.08

Commission's notes: 1. These wires were not cleaned before being connected. The remaining wires were cleaned with emery in oil prior to connection. 2. The data shown in this table are extracted from the original table.

K. Sato et al. (1976) carried out heat-cycling tests on copper, aluminum, and coated aluminum wires connected to Japanese duplex receptacles with and without pressure plates. In one test series, a brass binding screw and brass plate were used; a second test series used a brass binding screw with a brass plate against one side of the wire and a zinc-plated steel nut against the other side. Torque was varied from 6 to 10.4 lb-in. Currents of 40 amperes at 18 volts were circulated for 3/4 hour on/off for 2,000 cycles, and the temperature on the top of the screw was monitored. Failure was assumed when this temperature exceeded 175°C. After 2,000 cycles the voltage was increased to 70 volts. The results of the tests by K. Sato et al. are recorded in Table 22.

No failures were observed in copper-wire connections and there was only one failure (after 2,000 cycles) in the copper- and nickel-clad aluminum-wire connections. All three samples of aluminum alloy, torqued to 6 lb-in under a pressure plate, failed before 500 cycles but all other samples performed well at 10.4 lb-in torque and at both torques under the binding-head screw.

All EC-grade (fully hard) aluminum-wired connections failed before 500 cycles, as did all samples wired with EC-grade (half-hard) and torqued to 6 lb-in under a pressure plate. EC (half-hard) and EC (annealed) aluminum wire torqued to 6 and 10.4 lb-in under a brass binding screw did not fail but failure did occur in less than 500 cycles for both types torqued to 6 lb-in under a pressure plate.

These results demonstrated the improvement that coating can make in the connectability of aluminum conductors. Sato et al. further stated, "From the stability of the temperature rise, copper is superior to coated aluminum conductors." They also showed, by means of scanning-electron microscopy and electron-probe micro-analysis, that melting and transference of contact material took plate at the interface during failure.

(iv)   Crimp Connections. N.T. Bond and F.L. McGeary (1968) tested nonplated or cadmium-, copper-, nickel-, silver-, or tin-plated spade connectors of AWG-12 aluminum compression terminals connected to a rectangular bar of EC-H13 aluminum alloy with No. 10-32 nickel-plated steel machine screws and nuts torqued to 35 lb-in. Assemblies were aged two days, then given 50 oven cycles of 1 hour at 70°C. and 2 hours at room temperature, and, finally, 500 cycles at 30 amperes for 30 minutes on/off. The joint resistance was measured periodically, and was

constant and low ($\sim 20\ \mu\Omega$) for abraded aluminum, for non-abraded aluminum with joint compound, and for nickel-plated aluminum. Non-abraded aluminum without joint compound and cadmium-, copper-, silver-, and tin-plated aluminum showed increasing contact resistance (to $\sim 70\ \mu\Omega$) after ageing for two days at room temperature, and increased to over $100\ \mu\Omega$ (the acceptable limit) within 25 oven cycles to 70°C. These tests showed the superiority of a nickel-coated transition interface for joining to a bare aluminum surface.

J.H. Whitley (1964) pointed out that it was easy to obtain a low initial resistance in a pressure joint; a clean surface plus pressure were all that were necessary:

> The "trick is" to achieve a low resistance connection without special preparation of conductor surfaces, and to arrange to *maintain that low resistance* over the life of the joint, in adverse environments, and while it is being subjected to mechanical abuse. This, in essence, is the design problem in electrical connectors.

Crimped joints did not maintain a high residual force on the conductor but depended on the production of a sound metal-to-metal weld to establish and maintain electric integrity.

Whitley also pointed out that a crimp termination system could be optimized in several ways (e.g., lowest cost, highest reliability, greatest mechanical strength, widest range of wire size, highest temperature limits, best corrosion resistance, highest speed of application) and that not all of these could be optimized simultaneously. Therefore, a specific crimp system must be selected to suit the specific application "and that deviations from the tested and proven combination are likely to come back to haunt you — for the most 'unexpected' reasons."

T.H. Rice (1973) stated that "lack of a truly reliable and economic method of termination" was the one factor that had prevented wider industrial use of aluminum conductors. He claimed that the dry-crimp termination provided an economical, electrically and mechanically reliable connection for aluminum.

Table 22

HEAT-CYCLING TESTS ON PRESSURE PLATES
AND BINDING-SCREW CONNECTIONS

		Applied Torque	Pressure Plate		Binding Screw	
Type of Device			7 kg-cm	12 kg-cm	7 kg-cm	12 kg-cm
EC (H)			***	***	***	***
EC (Half-hard)			***	***	†††	†††
EC (0)			***	**†	†††	†††
Al alloy (0)			***	†††	†††	†††
Cu clad Al (0)			††*	†††	†††	†††
Ni plated Al (Half-hard)			††*	†††	†††	†††
Cu (0) 162 ϕ			†††	†††	†††	†††

*** Failure before 500 cycles
**† Failure after 500 cycles
††† Good (no failures)
††* Failure after 2,000 cycles
Commission's note: After 2,000 cycles the voltage was increased to 70 volts. Some failures were observed at the 7 kg-cm torque.

L. Dittman (1975) reported on a new "AMP Tamp" crimp terminal that used a wedge-shaped connector made of tin-plated aluminum or brass. The side walls were flexible and maintained the contact pressure on the aluminum wire and were said to overcome any problems of oxidation, creep, and galvanic corrosion.

Burndy Corporation, of Norwalk, Connecticut, began its development programme for aluminum and aluminum-to-copper connections in the early 1940's. The company has a range of clamp connectors — which use bolts, springs, or wedges to maintain contact pressure — and a range of compression connectors in which a simple compression tool establishes a good mechanical and electric contact.

Thomas & Betts Limited uses a jointing compound and a toothed compression connector which restricts longitudinal (tangential) flow of the aluminum conductor. This company in-dicates that the use of an aluminum connector is not practical because the proper yield-strength-hardness relationships cannot be achieved. Pressure connectors are a most reliable, convenient, and economical way of making electric connections, but the tools and techniques for use in branch circuits have not yet been completely developed.
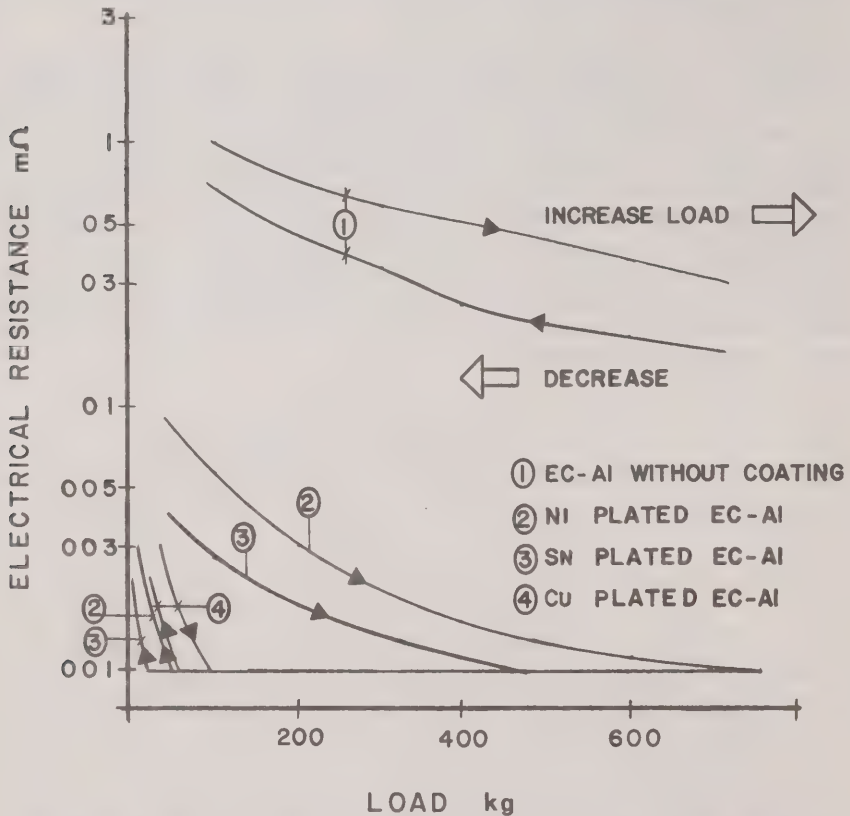
Figure 37.   Electric Resistance Versus Applied Load Between Aluminum Specimens and Brass

(v)   Contact Coatings. Particularly for contacts between aluminum and copper or brass, there are many advantages to coating the surface of either the conductor or the connector with gold, silver, tin, indium, cadmium, zinc, nickel, etc. Most of these metals are very ductile and can flow readily into cracks in either aluminum or copper oxide and establish metal-to-metal con-tact. Those with low melting points do not work-harden and, because they have low elastic moduli, do not have excessive spring-back which can fracture a-spots. They act in two other ways to prevent contact deterioration: they effectively protect the aluminum and copper from oxidation, and those that are intermediate between aluminum and copper on the galvanic series reduce the galvanic-cell potential and thus the risk of corrosion. The major problem introduced by the presence of these coatings is the formation of brittle high-resistivity intermetallic com-pounds which can seriously impair both the mechanical and electric integrity of the junction.

Although a great deal of research and testing has been carried out, a coating which is a universal panacea for all contact problems has yet to be discovered. Certain coatings are preferred for certain applications, and engineering judgement must always be exercised in selecting the most suitable coating for any given application.

Joint compounds or greases (some are simply vaseline with or without abrasive metal or oxide particles) are also used to retard corrosion and to minimize contamination during joint formation. Many investigations on surface coatings also measure the effect of joint compounds; these will now be considered.

K. Sato et al. (1976) demonstrated the effectiveness of copper, nickel, or tin coatings on EC-grade aluminum in reducing the junction resistance with brass. The shape of the resistance-versus-force curves shown in Figure 37 is similar to the theoretical and actual curves presented earlier. Copper, nickel, and tin reduce the contact resistance by more than an order of magnitude compared to uncoated EC aluminum, and they retain this superiority even on unloading to very low loads. A higher load is necessary on the EC aluminum coated with nickel or tin than that coated with copper to reach a limiting low-contact resistance.

W.F. Bonwitt (1948) tested cadmium, tin, and zinc coatings on bolted aluminum-to-copper connections. He subjected joints made with and without jointing compounds to elevated temperatures (to 200°C.) and to corrosive salt-spray tests, and measured the initial and final joint resistance. Initial and final values of approximately 10 to 20 microhms were observed on most cadmium- and tin-coated samples on heat cycling: very thin coatings of dry cadmium reached 182 $\mu\Omega$; dry, bare-aluminum wire, 146 $\mu\Omega$; and dry zinc (no joint compound), 490 $\mu\Omega$. After corrosion testing, the dry, zinc-plated specimen had a joint resistance of 162 $\mu\Omega$ and was still at the bottom of the ratings. But the ratings for cadmium and zinc used with joint compounds were completely reversed and both these coatings had the lowest resistance of $\sim$ 10 $\mu\Omega$. The tests illustrate the difficulty of attempting an overall or single-index material rating for an application where several variables (in this case, thermal and corrosion stability) must be considered.

Bonwitt considered that, because of the large increase in joint resistance (28.2 to 490 $\mu\Omega$), zinc failed the high-temperature test. This corroborated results obtained by Holm (1967) on screw contacts on aluminum and zinc. Although he gave no results, Holm stated that cadmium is similar to zinc in behaviour. Bonwitt's results showed that joint compounds alone were effective in establishing and maintaining low-resistance joints to copper even with bare-aluminum conductors, and even after exposure to elevated temperatures and corrosive environments for all the finishes tested except zinc. Only in the case of a flowed-tin coating on the copper could a stable low-resistance joint be established and maintained without a joint compound.

H.B. Gibson (1971) and D.C. Hubbard et al. (1954) showed the beneficial effects of silver, tin, cadmium, and zinc coatings on contact resistance. Hubbard also raised a very significant point on the necessity of sanding or wire-brushing aluminum conductors prior to installation in order to prevent joint damage by surge currents. "High-current tests on uncleaned, weathered conductors resulted in joint burn-down at the joint in every case. Cleaned conductors employing the same clamps withstood these surge currents without damage to the joint in every case." The latter effect is certainly related in part to the thickness of oxide film on aged aluminum, but it most probably results from the creation of asperities and a hardened surface layer containing oxide fragments which facilitate the formation of metal-to-metal junctions or a-spots. Hubbard also found that it was not necessary to clean copper connectors before joining; that joints with copper conductors ran cooler; that metal coating, if used, should have a minimum thickness of 0.005 inch; and that heavy, hot-flowed tin and cadmium coatings resisted corrosive attack most effectively.

In a discussion of Hubbard's article (published with the article), W.W. Loucks and J. Hus, of Ontario Hydro Research Division, reported on the superiority, after long-term atmospheric exposure, of tin-plated copper-to-aluminum connections over cadmium-plated copper-to-aluminum connections. Not only was the initial contact resistance lower with tin, but the superiority was maintained after two years' exposure.

R.B. Richardson (1957) evaluated plated coatings on the basis of exposure to salt spray, hydrogen sulphide, and outdoor and industrial atmospheres. He considered tin on copper superior in joining aluminum when no compound was used; cadmium on either copper or

aluminum was best for corrosion with low-contact resistance; nickel was superior to cadmium in tarnish resistance, but subsurface corrosion could occur in nickel-plated aluminum; zinc was an unsatisfactory contact material and did not maintain a low resistivity.

N.T. Bond and F.L. McGeary (1968) demonstrated that only nickel was a suitable transition interface to an uncoated aluminum conductor subjected to 25 oven-heat cycles of 1 hour at 70°C. and 2 hours at room temperature. Abraded and non-abraded aluminum with a joint compound were also satisfactory, but silver-, cadmium-, copper-, and tin-plated aluminum did not have contact-resistance stability and contact resistance increased above an arbitrary acceptable upper limit of 100 $\mu\Omega$.

B. Kountanis (1970) measured the contact resistance as a function of load and surface roughness for a wide variety of platings, conversion coatings, and jointing compounds. The data were presented in the form of individual charts for the chromium, nickel, and tin platings, and for the five conversion coatings and two joint compounds tested. He concluded that platings and joint compounds reduced the contact resistance below that of bare-aluminum surfaces; however, the contact resistance of platings was significantly lower (50 to 30 $\mu\Omega$) than that of a comparable aluminum sample with no joint (132 $\mu\Omega$). With a specimen loading of 300 psi, contact resistances of nickel, tin, and chromium platings were an order of magnitude below that of a bare-aluminum contact.

b. Installation. M.D. Bergan (1952) stated that to make a good electric connection to aluminum it was necessary to first apply an oxide-inhibiting compound and then wire-brush the surface through this compound. The cable should then be tightened in the connector and any compound removed from the insulation, since rubber may be attacked by the jointing compound. A tin-plate barrier should be used if corrosion was a problem. F.E. Sanford and J.I. Fisher (1958) noted that most connector problems could be traced to improper conductor preparation and to low torque. S.G. Ward (1954) reported that a large mass aluminum connector and the use of a paste containing zinc particles eliminated oxidation, corrosion, cold-flow, and differential-expansion problems.

The contact area must be large enough to prevent overstressing, creep, and stress relaxation. Since aluminum creeps at a much lower stress than copper, connectors for aluminum must be designed to insure a larger contact area and a correspondingly reduced contact pressure. The mass of the conductor must be large enough to maintain mechanical stability and to provide a heat sink and adequate radiating surface to minimize temperature build-up. The relative strengths and hardnesses of the oxides, the metal matrices, and the metal surfaces must be modified or controlled in order to establish good metal-to-metal contact. These factors are not well understood but, in general, friable oxides and metals that are soft enough to flow readily are preferred.

E. W. Perry, Jr. and H.B. Gibson (1972) stated that only connectors that were compatible with aluminum conductors should be used. If only copper-compatible connectors were available, a suggested solution was the splicing of a segment of copper wire to the aluminum conductor with a compression connector specifically designed for this application. They believed that contact failures were invariably the result of improper installation and urged that oxide on the conductor be removed by wire brushing through a paste joint compound with or without metallic particles. Perry and Gibson suggested that Belleville compression washers be used in heavy-duty service to compensate for conductor creep and stress relaxation. They also pointed out that one equipment manufacturer recommends that "all mechanical lugs must be retightened after the equipment has been in service long enough to operate under full load conditions."

Underwriters' Laboratories, Inc., Canadian Standards Association, Ontario Hydro, Alcan, IEEE, and NEMA have published brochures that describe the correct installation procedures to be employed with aluminum conductors. In branch-circuit sizes the solid conductors must be used with approved connectors, and the wire in binding-screw terminations must be properly wrapped around the wire binding-screw post and must be torqued to 12 lb-in to break the oxide film and insure adequate metal-to-metal contact. Surface preparation of the conductor or use of a joint compound is neither required nor recommended. On the other hand, for stranded-aluminum conductors or for solid conductors that are used in damp locations, wire brushing under a grease or jointing compound — to restrict the access of oxygen and water — is a preferred method of joint preparation. This treatment reduces the thickness of oxide, fragments the oxide, and work-hardens and roughens a surface layer. This facilitates plastic flow at asperities and, for a given

normal load, insures that relatively larger areas of metal-to-metal contact are formed than would be the case for smooth surfaces with thick, high-resistance oxides and contaminating films. At relatively low normal loads, a tangential component greatly increases the metal-to-metal contact area. This is particularly important in aluminum where very high normal forces can cause excessive cold flow. If galvanic corrosion is a problem, it may be necessary to insert a layer of plating between an aluminum conductor and a brass or copper fitting.

2.5.6 Canadian Service Experience and Testing of Connections

Investigation and testing of overheated devices in branch circuits wired with aluminum and copper conductors, and fundamental contact studies have been reported by Ontario Hydro, the Canadian Standards Association, Hydro Quebec (IREQ), and the Aluminum Company of Canada, Ltd., Research Centre, Kingston. Results from Canadian and United States laboratories are discussed in detail in Section 2.6. However, for completeness and perspective in this section, some of the results of these tests and studies are also summarized below.

a. *Ontario Hydro.* Personnel from operating and research branches of Ontario Hydro have provided a great deal of information from field studies, laboratory testing, and metallurgical examinations of failures on a wide variety of devices used in branch circuits.

J.E. Morey and K.A. Sharp (1977), electrical inspectors in the Ottawa region, testified (Exhibit 109) that loose screws, which were due mainly to the use of pump screwdrivers, were chiefly responsible for the failures in aluminum-wired receptacles. There have been no recalls to homes where Ontario Hydro personnel tightened the screws. Similar problems were not encountered with copper wiring. It appears, therefore, that there were many failures due to loose connections in the Ottawa area.

Although Mr. Sharp did not so testify, the Ontario Hydro Research Division report on failed duplex receptacles from the Ottawa area showed that overheating also occurred in many receptacles in which the screw connections appeared to be tight on visual inspection.

R.T. Whiteford, Supervising Electrical Inspector, Brampton area, reported (Exhibit 153) on overheating problems in aluminum-wired receptacles and also on the trouble-free operation, since 1966, of some aluminum-wired homes in Bramalea. He supplied data from the company that had wired a major development project in Central Park, Bramalea. Here 60,000 receptacles were installed with only six calls back. Twenty-thousand panels were installed, and four complaints were attributed to faulty circuit breakers. A few failures were attributed to poor workmanship and to defective wiring devices, but overloaded circuits created most of the problems.

L. Stoch, Electrical Inspection Superintendent, Central Region, reported (Exhibit 162) on several overheated receptacles, three panelboard failures, two small fires associated with aluminum-wired receptacles, and four fires associated with copper wiring (one receptacle, one light fixture, one wall thermostat, and one unknown). He testified that in several cases circuits had been overloaded and that frayed extension cords had caused short circuits.

Stoch's testimony indicated that factors other than initially loose screws were responsible for failures. Circuits had been overfused and, therefore, could have been subjected to higher-than-allowable currents. Panelboard design created problems and short circuits did occur.

F.P. Kehoe, Supervising Electrical Inspector in the London area, reported (Exhibit 193) that there had been 14 residential aluminum-wiring receptacle problems since 1974. Thirteen were push-in type receptacles, and one was a CO/ALR type in which arcing occurred at a loose neutral screw. There were no reports of any other problems with CO/ALR receptacles. Of three house fires investigated in which receptacles were involved, two homes were copper-wired and one aluminum-wired. It would appear that a loose connection and push-in receptacles were the major problems in the London area.

Ontario Hydro Exhibit 44A, *Residential Wiring Research Program Detailed Results,* by R.L. Hicks, on the basis of a statistical analysis of field failures, concludes (p. 129): ''. . . this means that connectors (and receptacles) will continue to fail for a long time.'' The following factors were said to have contributed to failures in electric connections wired with EC-grade aluminum:

1. Loose terminals. Originally loose terminals have a high contact resistance and a shortened life. Receptacle screws can become loose when the receptacle is pushed back into the box or when the electrician fails to apply sufficient torque. No evidence of creep or stress relaxation has been observed by Hydro.

   Pigtail connectors with steel springs, joined with a low torque to aluminum wire, are particularly prone to failure. In a newly designed special-service connector, a copper-alloy spring replaces the steel spring used in the present pigtail connector. Copper wire is now mandatory for connections to baseboard heaters.

   Backwired receptacles presumably show overheating because a low contact pressure results in a high contact resistance.

   Design in some panelboards does not provide adequate force on contacts.

   Workmanship, in the form of improperly made wire loops, failure to use no-oxide paste, ringing of wires, use of illegal devices, and illegal wiring practices.

2. Zinc-plated terminals. Note that Hicks states (p. 27), "The higher torque could more than compensate for the use of unsuitable connector materials."

3. Overloading of circuits increases the operating temperature and shortens the time to failure.

4. The mechanical rigidity of the receptacle connection is reduced when the break-off tab is removed.

5. Unpublished studies elsewhere suggest an abnormally long storage period following manufacture as a possible cause of failure of bare-brass terminals.

6. The extent of the following factors' effect on connection life is unknown:
   (i) oxide formation
   (ii) intermetallics
   (iii) differential thermal expansion
   (iv) torque
   (v) plastic degradation
   (vi) fretting
   (vii) thermal ratcheting
   (viii) creep
   (ix) transverse stress relaxation
   (x) temper
   (xi) temperature stability of aluminum wire

7. Unknown phenomena.

Table 23

SUMMARY OF OVERHEATING INSTANCES

Screw Surface Material	Conductor	
	Al (EC-grade)	Cu
Zinc	34/54	2/10
Nickel	6/15	0/3
Tin	0/30	0/4
Indium	0/8	0/2
Silver	0/6	–
Brass	6/113	0/19

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Commission's notes: 1. Duration of test, 2,500 cycles. 2. In each column entry, the first number is the number of failures, the second number represents the total number tested in each group, i.e. 34/54: 34 failures, 54 tested.

Ontario Hydro Research Division Report 75-226-K, dated June 5, 1975, found that at high currents duplex receptacles overheated when connected to aluminum wire (EC H14) and did not overheat when connected to copper wire at torques of 6 lb-in. Temperature was measured at the break-off tab on cycling a current of 27.5 amperes for $3\frac{1}{2}$ hours on and 1/2 hour off 500 times. Failure was assumed when the break-off tab temperature reached 200°C. One hundred and twenty-two receptacles were tested and 36 with zinc- or nickel-plated terminals overheated; two unplated terminals overheated. No overheating was observed in terminals coated with silver, indium, and tin. The masses of the receptacles tested varied between 28 and 96 grams and could not be correlated with performance. Backwired receptacles wired with either aluminum or copper also overheated.

Ontario Hydro Research Division Report 76-189-K, dated April 28, 1976, gave the results of continuing the heat-cycling tests to 2,500 cycles. The previous poor performance of nickel and zinc was confirmed (even in two cases of zinc with copper wire), while no failures were observed with silver, indium, and tin coatings. Six out of 113 unplated brass screws overheated. A summary of overheating results is given in Table 23.

In Ontario Hydro Research Division Report 76-387-K, R.L. Hicks discussed the effect of appliance starting currents on residential wiring connections. The highest instantaneous peak current measured was 76 amperes on starting air conditioners, although 150 amperes was measured on some 230-volt appliances. It was concluded that the duration of the surge current was too small to affect the bulk-connector temperature and should not cause localized (a-spot) heating. This latter conclusion was based on the assumption that the contact resistance was below 1,100 to 1,600 $\mu\Omega$. Unpublished values of 400 $\mu\Omega$ were suggested as being realistic. A very important conclusion was that short-circuit currents may permanently alter the connector-interface geometry but there were insufficient data to assess whether such currents would affect connector life.
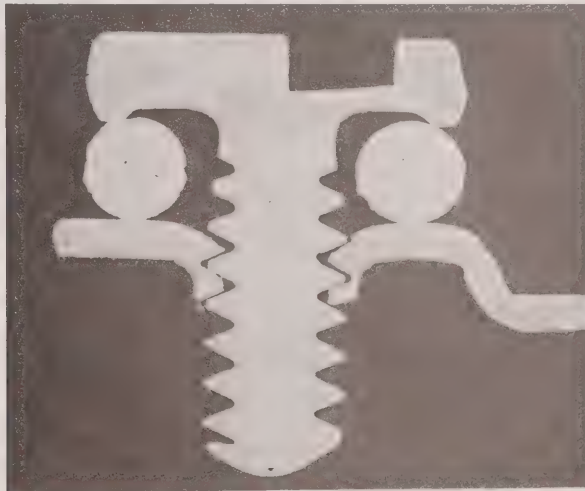
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Figure 38.   Overall View of Prepared Neutral Connection
(7.5x magnification)

Ontario Hydro Research Division Report 76-14-H, dated January 13, 1976, *Metallurgical Examination of Failed Receptacles Wired with Aluminum*, established that overheating in service produced temperatures high enough to recrystallize and soften cold-worked aluminum and brass components (greater than 300°C.). Six overheated receptacles from the Ottawa area and four new receptacles with different plating materials (zinc, silver, nickel, indium, tin) were examined. In Figure 38, a typical binding-head screw connection is shown at a magnification of 7.5 times,

while the interface between the screw and the aluminum wire at a magnification of 150 times is shown in Figure 39. No appreciable flow of coating metal is visible on the screw.
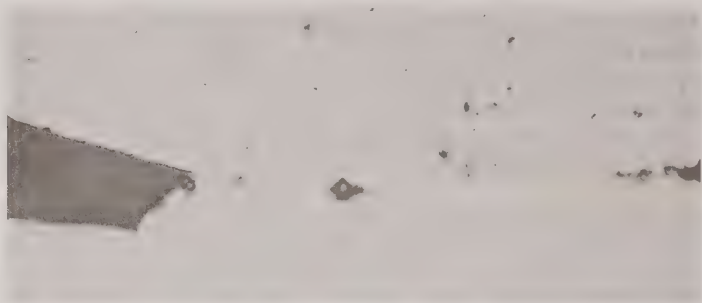
Figure 39.   Screw Plating to Aluminum-Wire Interface (150x magnification)

Fretting damage was found on only one silver-coated aluminum wire, as shown in Figure 40. No fritting damage was found.
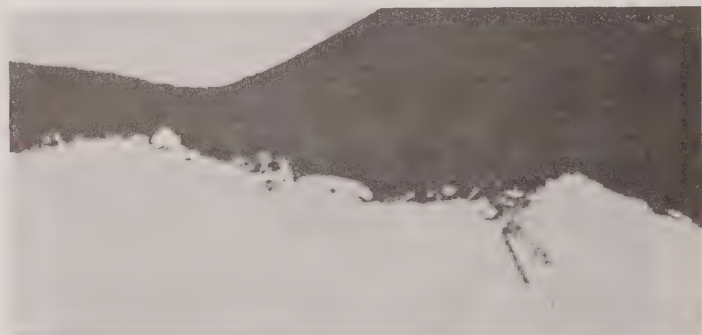
Figure 40.   Fretting Damage on Aluminum Wire at Screw Contact Surface (200x magnification)

Figure 41.   Surface Dezincification of Brass Screw (250x magnification)

Dezincification occurred at the surface of the brass screw from an overheated receptacle, as shown in Figure 41 at a magnification of 250 times.

Figure 42.   Cold-Drawn Aluminum Wire (38x magnification)

Figure 43.   Overheated and Recrystallized Aluminum Wire
(38x magnification)

A section of aluminum wire from a cool region is shown in Figure 42, and from an overheated region in Figure 43; a cold-deformed section of brass is shown in Figure 44, and an overheated, recrystallized section in Figure 45. There was a corresponding lowering of hardness in the heated regions. None of the screw plating materials appeared to have diffused into the aluminum wire.

In an Ontario Hydro Research Department report to the Commission, dated January 1978, M. Léger calculated (Exhibit 195) the time required to form a 350,000 nm.-thick intermetallic

layer between aluminum and brass at 50°C. as 5.7x10^{13} hours or more than six billion years. A 24.1 nm. layer would form in 30 years at 50°C. and the resulting increase in contact resistance would be minimal. The effects of higher temperatures, surface or grain-boundary diffusion, zinc vaporization, or the formation of other reported intermetallic species and phenomena on contact resistance were not considered.

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Figure 44.   Cold-Deformed Structure of Brass Screw Head
(250x magnification)

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Figure 45.   Overheated and Recrystallized Structure of Brass Screw Head
(250x magnification)

Léger also made a metallurgical examination of a steel binding-head screw that had locally overheated on one side of a duplex receptacle at No. 798 Cabot Trail, in Milton (Research Report 77-551-H). He concluded that this type of damage required contact deterioration and the passage of a current. The aluminum wires had recrystallized at three of the four binding-head screw connections to the duplex receptacle. The microstructure and hardness tests indicated that a temperature of 300°C. was reached on the neutral side of the receptacle and 400°C. to 600°C. on the live side. Although the wires were pitted and rough — indicating the possibility of either or both corrosion and electric damage — there was no sign of melting and no evidence of alloying. The brass base plate on only the live side of the receptacle had started to recrystallize, and dezincification of the plate was observed adjacent to one of the steel binding-head screws. The microstructural and hardness studies indicated temperatures of 400°C. on the live side and 300°C. on the neutral side of the receptacle.

The steel screws were originally cold-formed from low-carbon steel and the head of only one screw on the live side of the duplex receptacle had recrystallized. Léger concluded that only an electric source of heat could localize the heat in this manner, and he estimated that a temperature of 600°C. was required to cause the degree of recrystallization observed. Heating a screw for 1 hour at 600°C. in a furnace did not duplicate the observed microstructure in which most of the carbides were found at the grain boundaries. By measuring the distance from the screw head to the brass plate on the receptacle, the torque on the screw heated to 600°C. was estimated at 3 lb-in, which suggested that the most severe overheating was at a loose connection.

Three other steel screws associated with the receptacle were examined. Two steel screws inside the face plate, holding the receptacle in place, had not recrystallized; presumably they were sufficiently shielded from the fire. The head of the steel screw that held on the face plate had recrystallized; presumably it was not shielded from the fire.

In Ontario Hydro Research Division Report 78-37-H, dated January 31, 1978, M. Léger made a metallurgical study of components from an aluminum-wired baseboard heater. The components were from 3 Gladstone Square, Bramalea, where there had been a fire at the end of April 1977. The aluminum fins on the heater had melted, indicating a temperature above 660°C. Three pigtail connectors from the heater were examined and flame tests and high currents were used in the laboratory to simulate the structures observed in the "failed" connectors. Two copper wires joined by a pigtail in the Gladstone Square heater had surface grains smaller than the interior grains, and there were voids and oxides at the grain boundaries and within some grains. No plastic insulation remained on the connector. Two connectors joining solid aluminum to stranded copper still had some plastic insulation in place. There were fewer voids and oxide particles than in the first copper wires examined, and the surface grain size was finer. The aluminum wires had large, recrystallized grains, and alloying had taken place between the aluminum and the copper wires.

Overcurrents in the laboratory developed alloying between copper and aluminum but severe oxidation of the copper wires left only small, irregular cross sections of wire in place in the connector. This test also recrystallized all aluminum and copper wires to varying degrees. Pigtails burned in a Bunsen burner for 4 minutes produced alloying in a solid-aluminum-and-stranded-copper-wire connection. A very significant observation in this investigation was that in electric failures in stranded-copper-to-solid-aluminum connections there was localized gross oxidation of the copper-strand cross sections that was caused by intense heating of short duration. However, it was concluded that all damage to the baseboard heater from Gladstone Square could be attributed to the fire.

An Ontario Hydro survey of field failures associated with aluminum wiring in the Toronto area (Research Division Report 75-47-K, dated January 30, 1975) found that 18 of 22 failures were in push-in receptacles wired to aluminum. In 20 of 22 instances, damage was confined to the receptacle; in one case, sparks spewed onto a rug with no ignition; and in another instance, a bedspread and mattress 6 inches from the receptacle were slightly charred.

Ontario Hydro Research Division Report 76-191-K, dated April 30, 1976, concluded that pigtail connections between solid-aluminum and extra-flexible, bare-stranded copper wire (41 strands of AWG-30 wires in an AWG-12 conductor) were less reliable than pigtail joints between solid-aluminum and solid-copper wire. The report recommended that ". . . presently available pigtail

connectors should not be used to join solid aluminum and extra flexible bare stranded copper wire in the supply to heavy current appliances in new installations." Only installation and workmanship parameters were considered; no attempt appears to have been made to evaluate any design or material reasons for the poor connector performance.

Ontario Hydro Research Division Report 77-100-H, dated February 28, 1977, which was transmitted to the Commission on February 6, 1978, compared the corrosive action of fibreglass and urea formaldehyde foam in simulated wall enclosures containing three different types of receptacles wired to both aluminum and copper conductors. The report showed that, compared to fibreglass insulation, one type of urea formaldehyde foam caused a significant degree of corrosion to zinc plating on both steel and brass but it did not affect the electric performance during a 28-day humidity exposure (49°C. and 95% relative humidity).

Ontario Hydro carried out a series of tests on fuse and breaker panelboards in which they identified design problems and also established that fuse-plug contact temperatures were a function of fuse-tightening torques. In these laboratory studies they were also able to show (Ontario Hydro Research Division Report 75-177-K) that ". . . loosening torques for plug fuses decrease as the panelboard is used" and this supported field observations that fuse torques were lower in heavily loaded circuits (heating and split-receptacle circuits). The report concluded that the fuse was a major contributor to heat in freshly made circuits and that contacts were a major source of heat in "aged" or current-cycled circuits. It was found that the plastic around the fuse nipple deformed, causing a loss in contact pressure and a consequent rise in contact temperature.

Heat-cycling tests (1/2 hour on/off at rated current in all circuits) showed that higher temperature increases occurred when panelboards were wired with aluminum than when wired with copper and that proper workmanship was a major factor in the aluminum connections. Thus, when the aluminum wire was properly cleaned and a joint compound used with high installation torques, lower termination temperatures were observed in 125-ampere circuits than in 100-ampere circuits in which proper workmanship procedures were not so strictly observed.

In cyclic tests at rated voltage, a residential panelboard showed both a large increase in voltage drop across the main breaker (see Table 24) and a fluctuation in voltage drop, which could cause flickering of lights. There was a supply-side connection failure and degradation of insulation on the supply conductors as well as emission of sparks from the main breaker. The main-breaker temperature rose to 162°C. after 675 cycles. Temperatures of 266°C. and 349°C. were observed at 725 cycles on the two supply-side terminals of the main breaker. The insulation softened and flowed at the latter temperatures.

Table 24

VOLTAGE DROP ACROSS MAIN BREAKER AT 80 AMPERES

Main Breaker	Side L_1		Side L_2	
	0 Cycles	725 Cycles	0 Cycles	725 Cycles
Voltage Drop mV	98.4	870.0	83.6	111.0
Heat Loss watts	7.9	69.6	6.7	8.9

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b. *Canadian Standards Association.* The Canadian Standards Association Task Force on Aluminum Terminations and the Working Group on Branch Circuit Wiring — which included personnel from Ontario Hydro, Hydro Quebec, Alcan Canada Products Limited, and Canadian cable and electric-device manufacturers — utilized information provided by these organizations. The Working Group's report of May 18, 1976 included Table 25, an Ontario Hydro summary of aluminum-wired receptacles that had failed in service.

Three quarters of the receptacle failures occurred at zinc-plated identified terminals, and one quarter at brass unidentified terminals. About one half of the failed receptacles had loose wires on overheated terminals and about one half did not. One quarter of the failed receptacles were connected to split receptacles, and preliminary tests indicated that this made motion easier at the

contact interface. Half failed before two years' service and half failed after two years' service. Ontario Hydro and Hydro Quebec metallurgists found indications of fretting, intergranular fracture, and unforeseen dezincification of the brass, but no specific conclusions were drawn on factors leading to failure.

Table 25

STATISTICAL SUMMARY OF FAILED RECEPTACLES

1	Location of Most Severe Overheating	
	Identified terminal (zinc plating)	76
	(silver flash)	10
	Unidentified terminal (brass)	29
	Both terminals	11
	Internal	1
	Backwired (push-in)	11
2	Condition of Overheated Terminal	
	Wire loose	70
	Wire tight	62
	Indeterminate	6
3	Application of Receptacle	
	Break-off tab removed (split-wired)	32
	Break-off tab present	106
4	Age of Dwelling	
	0 - 1	4
	>1 - <2	60
	>2 - <4	39
	>4	21
	Not known	14
5	Receptacles with Push-in Connections	11
6	Number of Receptacles not Withstanding 500 V Voltage Withstand Test	
	Screw connection	1
	Push-in connection	1

Alcan and Ontario Hydro Research Laboratories also reported (see Table 26 and Figure 46) the results of high-current heat-cycling tests on receptacles wired to EC-aluminum, aluminum-alloy, and copper conductors in which the brass screws were plated with a variety of metals. It was concluded that indium and tin were the best, and zinc and cadmium were the worst, contact-interface materials. Under these particular test conditions, there was no noticeable difference between the performance of copper and aluminum with indium-plated connections.

The histogram (Figure 46) of results of Ontario Hydro's tests shows that half the failures occurred in the first 150 cycles. However, no relation between the early failure rate and service failures could be drawn except that the rate of failure would decrease with time.

At the request of Phillips Cables Ltd., British Insulated Callender's Cables Limited (BICC Ltd.) conducted heat-cycling tests (15 amperes for 5 hours on and 1 hour off) on various Canadian Standards Association-approved devices connected to EC-aluminum, iron-enriched aluminum-alloy, copper-clad aluminum, and copper wires. They found that, after 22,000 to 27,000 hours of testing:

1. Brass binding-head screw connections, torqued at 7.5 to 10 lb-in, did not overheat with any of the conductor materials tested. However, after only 2,000 hours of testing at 15 amperes, there were several failures of aluminum and aluminum-alloy conductors at binding-head screw connections torqued at 2.5 to 5.0 lb-in.
2. Push-in connections overheated with all conductors, including copper.
3. Wire connectors showed more erratic performance. In 15,000 to 18,000 hours of testing there was no overheating when both wires were copper but there sometimes was over-
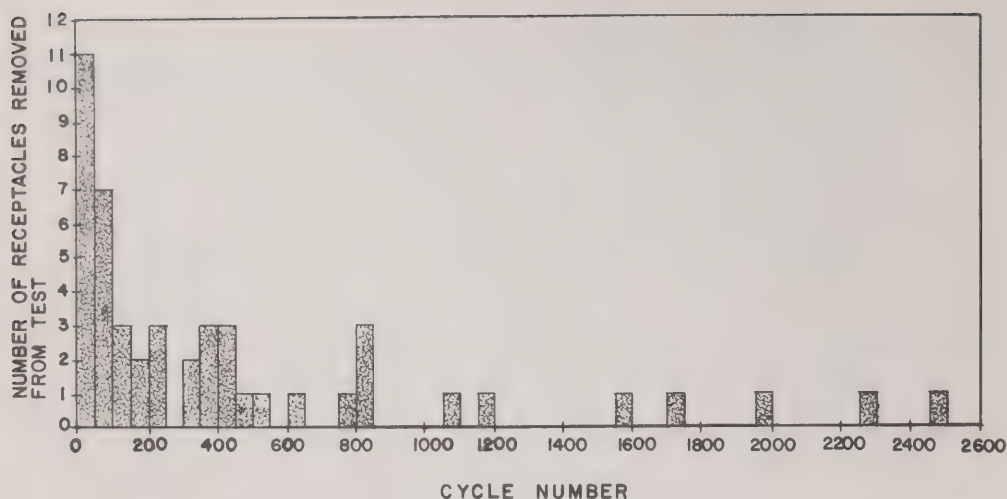
Figure 46.   Histogram of Overheating Connections

Table 26

SUMMARY OF TEST DATA ON RECEPTACLE/WIRE CONNECTION PERFORMANCE

(Entries are ratio of failures to number tested in each group)

Receptacle Terminal	Alcan No. 1 (2)		Alcan No. 2 (3)			Ontario Hydro (4)	
	Aluminum		Aluminum		Copper	Aluminum EC	Copper
	EC	Alloy	EC	Alloy			
Brass binding-head screw surface material:							
Zinc (5)............................	13/30	7/35	10/10	9/10	6/10	27/54	1/10
Cadmium.........................	6/10	7/10	–	–	–	–	
Nickel	0/10	0/10	–	–	–	5/15	0/3
Silver	0/10	0/10	6/10	0/10	0/10	0/6	–
Brass (6, 9)......................	0/70	0/70	4/40	0/40	1/40 (10)	2/113 (8)	0/19
Tin (5).............................	0/5	0/5	1/10	1/10	0/10	0/30	0/4
Indium (7)........................	0/5	0/5	0/10	0/10	0/10	0/8	0/2
Push-in.................................	–	–	–	–	–	5/5	2/2

NOTES:

1. Test Condition: Current on 3-1/2 hours, off 1/2 hour; screw tightened to 6 pound-inches; 3/4 loop in wire; thermocouple on break off tabs.
2. Test Condition: Current 25 amperes; results after 1000 cycles; no wire disturbance; mounted in open air. Failure criteria rise to 100°C above ambient.
3. Test Condition: Current 40 amperes; wire disturbance applied at 25th and 125th cycle; results after 500 cycles. Failure criteria was rise to 100°C above ambient or loosening of screw during wire disturbance.
4. Test Condition: Current 27.5 amperes; mounted in boxes; results after 500 cycles; no wire disturbance. Failure criteria was rise to 200°C.
5. Plating material is that on screw. Terminals in some instances were bare brass.
6. Brass on both screw and terminal or on screw alone with plated terminal.
7. Indium on both screw and terminal.
8. Failures involved brass screw and bronze terminal.
9. Complete receptacle was removed when a terminal overheated. Thus not all intact brass terminals experienced 500 cycles.
10. This particular failure involved a brass screw and an indium plated terminal.

heating when one or both conductors were aluminum. Mild steel was shown to be unsuitable for grubscrews but overheating was not observed with EC-grade aluminum conductors connected in brass tunnels with brass grubscrews.

c.   Hydro Quebec, Institute of Research (IREQ). M. Braunovic, Senior Scientist, in *Causes of Electrical Instability in Electrical Contacts with Aluminum Conductors* considered (Exhibit 236) that:

1. Oxidation by itself was not likely to cause failures in aluminum, since the oxide thickness is ∼100 Å and the contact diameter 1,000 to 10,000 Å. Oxidation was not self-limiting in copper and could cause contact failures.
2. Fretting could lead to progressive contact degradation and also could accelerate other processes, such as creep and the formation of intermetallics. Fretting was less damaging with copper than with aluminum.
3. Creep was greater in aluminum than in steel or copper and increased with increasing temperature.
4. Stress relaxation lowered the pressure on the contact more on EC-grade aluminum than on copper and even more on hard-drawn EC aluminum.
5. There was an electroplasticity effect whereby the electric and magnetic fields influenced the plastic properties of the contact metals. There were few data on how, or to what extent, the rate of creep and stress relaxation could be altered by this phenomenon.
6. Thermal ratcheting loosened the contact between aluminum and brass because of the difference in coefficients of expansion.
7. Whether intermetallics caused overheating or were formed by overheating has not been established.

d.   Aluminum Company of Canada, Ltd., Research Centre, Kingston, Ontario. The Research Centre has investigated laboratory and service behaviour of connectors wired to both aluminum and copper conductors. In co-operation with the Canadian Electrical Association the Centre is carrying out a fundamental study of electrical connections involving aluminum wire.

An *Examination of Aluminum Wired Receptacles After 28 Years' Service in Arvida Houses* was reported in Aluminum Company of Canada, Ltd. Research Report KR-78/006-S, dated January 19, 1978, by K.J. Smith and R.S. Timsit. Two receptacles that had been wired with AWG-12 aluminum wires and one that had been wired with AWG-14 copper wires were studied visually and by optical and scanning-electron microscopy, with the following results:

1. One loose screw was found on the neutral terminal of each of the three receptacles. There is no comment in the report on whether the screws were loosened in service or by mechanical abuse or whether they were not tightened initially.
2. No intermetallics had formed. The receptacles were not believed to have overheated, since the rubber insulation on the aluminum wires was still soft and pliable although that on the copper wires was hard and brittle.
3. Dezincification of brass occurred with both aluminum and copper wiring. The zinc did not diffuse into either the aluminum or copper wire and "it is surmised that this zinc condensed on cool sections of the brass surface away from the contact zone when the junctions were in operation."

Alcan Report KR-77/104-S, *A Review and Evaluation of the Properties of Electrical Contacts Involving Aluminum and Copper,* by R.S. Timsit, dated December 5, 1977, discussed (Exhibit 187) contact-degradation mechanisms:

1. Destructive oxidation of aluminum a-spots at temperatures below 100°C. was prevented because the growth of the oxide (Al_2O_3) film was less than 100 Å at these temperatures. Timsit believed the same argument applied to copper and brass.
2. Fretting could be caused by differential thermal expansion between aluminum and brass or other dissimilar metals in contact. Timsit believed that this mechanism should operate to the same extent in both aluminum-brass and copper-brass contacts.
3. Growth of high-resistivity intermetallic compounds in the aluminum-brass system would occur but growth of a 5-μm layer would take ∼150 years at 100°C. — assuming approximately equal diffusion rates in the aluminum, brass, and copper-brass systems — whereas

an intermetallic layer of ~50-μm would be required to give a resistance close to that of the constriction resistance (~$10^{-4}\Omega$). Thin layers of intermetallics, however, could increase contact brittleness and would increase susceptibility to mechanical damage, including fretting.

4. Creep and stress relaxation would only become significant if they led to micromotion and fracture of a-spots. Data to assess this effect were not available.

CEA/Alcan Sponsored Contract No. 76-19, *Study of Electrical Connections Involving Aluminum Wire,* Progress Report No. 2, dated April 30, 1978, by K.J. Smith, R.S. Timsit, and W.C. Fraser reported that a-spots in EC-aluminum-to-EC-aluminum contacts grew by sintering when heated in vacuum at temperatures between 20°C. and 400°C. Growth due to volume diffusion predominated between 100°C. and 350°C., while plastic flow appeared to control the sintering process at lower temperatures. A-spot growth did not appear to be related to surface diffusion or viscous flow. A very interesting experiment — in which the contact load was reduced from 400 grams to 60 grams on EC-grade aluminum contacts in vacuum — showed that only at the lowest load was there a decrease in the size of the a-spots and a corresponding increase in resistance. In these experiments a-spot growth occurred as the load was removed. This was attributed to the generation of new a-spots by mechanical disturbance when the load was removed. Oxide films and magnitude of applied load had no effect on this behaviour.

Thermal runaway was observed in aluminum contacts in vacuum whether or not oxide films were present. In a typical case, with 13.6 amperes flowing through a junction with 68-millivolt voltage drop, a junction temperature of 100°C. was observed. After 20 minutes' operation the a-spot radius (originally 3.5 μm) decreased by 13% and the contact temperature increased 30°C. After 27 minutes the contact temperature increased to 175°C., the metal softened, and B-fritting increased the a-spot area, reducing the voltage drop and the contact temperature to 100°C. (It is of interest to note that although the ratio of $\ln\left(\frac{r}{r_0}\right)$ changed from an initial 0 to 0.4 after thermal runaway, the operating temperature of the junction both before and after was the same at 100°C.) The failure mechanism was unknown but it was postulated that formation of solid intermetallic particles ($FeAl_3$, Fe, Fe-Si-Al compound), voids, or oxides at the interface could be responsible. Electron-microprobe analysis detected carbon and oxygen in the interface region.

The cracking of an Al_2O_3 film 286-Å thick by a spherical glass indenter (2.5-mm. radius) produced a random-crack network with crack thickness estimated to be only a few tens of angstroms (i.e., much lower than the 500- to 5,000-Å radius estimated for a-spots).

Hemispherical surfaces of clean (ion-etched) EC-grade aluminum wire were brought into contact in a 2×10^{-10} torr vacuum, and contact growth was observed at 20°C. Pure oxygen gas was introduced and caused, in a typical case, cessation of contact growth and an immediate 34% decrease in contact radius. Heating to 450°C. did not result in contact growth by sintering as previously described. No thermal runaway has been observed in an oxygen atmosphere even at the highest junction temperatures tested.

The contact resistance before surface-film rupture was greater than 10^7 Ω and quantum tunnelling could not be detected. At a load of 100 grams the contact radius was 1.2×10^{-2} cm. The oxide film broke down initially at higher than 4 volts but dropped to very low values after several make-break contact cycles. Junction growth was erratic in the presence of oxide films and may have been affected by vibration. Junction growth was not measured as the only sample tested suffered thermal runaway after a few hundred minutes of operation. A current of only 0.146 ampere was sufficient to raise the junction (radius ~7×10^{-6} cm.) temperature to 67°C. As the contact radius decreased, the temperature rose to ~172°C., where B-fritting increased the contact area and lowered the resistance and the temperature to 27°C. At ~1,300 minutes of the test the junction, for unknown reasons, shrank again, the junction temperature jumped to 150°C., and the contact suffered thermal runaway. A preliminary microprobe analysis of the aluminum contact spot showed the presence of carbon and zinc and, on the brass contact spot, a concentration of carbon and oxygen. The factors that triggered runaway were unknown but the formation of oxides or other insulating films at the interface — caused by diffusion of dissolved oxygen or decomposition of volatile, subsurface oxygen-carrying compounds — was suggested.

The diffusion between EC aluminum and α-brass (70% Cu, 30% Zn) has been measured at 250°C. and 350°C. and the increase in thickness of the intermetallic layer (h) is given by:

$$h^2 = k(T)t \tag{26}$$

$$t = \text{time}$$
$$k = \text{function of temperature}$$

$$k = k_o \exp\left(^{-Q/RT}\right) \tag{27}$$

$$Q = \text{activation energy for intermetallic}$$
$$\text{growth (cal/mole)}$$

Where preliminary data give

$$k = 3.46 \times 10^{-4} \exp\left(^{-22,100/RT}\right) \tag{28}$$

The scanning-electron microscope analyses showed that copper diffused from the brass into the aluminum but little aluminum diffused into the brass.

The diffusion of indium, tin, and zinc platings into brass (70% Cu, 30% Zn) was measured in the temperature range 80°C. to 150°C. The constants k_o and Q for the coefficient k are given in Table 27.

Table 27

DIFFUSION CONSTANTS FOR
METALS IN BRASS

Metal	k_O (cm^2 sec^{-1})	Q (kcal mol^{-1})
Zinc	69.1	22.9
Indium	1.25×10^{-7}	9.72
Tin	5.18×10^{-9}	7.88

CEA/Alcan Sponsored Contract No. 76-19, Program B, Progress Report No. 2, reported on the measurement of the mechanical properties of an EC-grade aluminum, an aluminum alloy, and a copper conductor, as given in Table 28.

Table 28

TENSILE PROPERTIES OF WIRE

Wire	Diameter		Ultimate Tensile Strength		Yield Strength (0.2% Strain)		Elongation % in 250 mm
	mm	in.	kPa	ksi	kPa	ksi	
AA 1350 (EC)	2.06	0.081	117	17.0	98	14.3	16.1
CA 10920 (Alloy)	2.06	0.081	118	17.1	88	12.8	20.6
Copper	1.65	0.065	249	36.1	174	25.0	27.8

Commission's notes: 1. The values shown in this table are an average of tests performed on three specimens.
2. The metric values for the wire diameters have been calculated by the Commission.

The torque-load resistance characteristics of binding-screw terminations were studied with and without lubrication. Aluminum and copper wires were connected to indium-, tin-, and zinc-plated and bare-brass terminals at 6 to 12 lb-in torque. Low contact resistances (0.2 to 0.4 mΩ) were measured in all cases even though the contact force ranged from 30 to 200 pounds. Higher forces were measured with lubrication but there was no significant reduction in the contact resistance.

The relationship between connection life and current-cycle period is being investigated, using AA 1350(EC) aluminum conductors connected to receptacles with bare-brass terminals. To date these have withstood 1,200 cycles at 45 amperes for 1^1/$_2$ hour on and 1/2 hour off, and more than 600 cycles for 3^1/$_2$ hours on and 1/2 hour off, with no sign of overheating. Only two receptacles in each test had temperature increases in excess of 10°C. Samples now in storage will be used to study the influence of shelf life on connector performance.

2.5.7 Contact Degradation and Failure

This section discusses contact degradation and failure in nominally static electric contacts. Although no published study of progressive deterioration of static contacts was found, there were some reports of examinations of contacts that failed in service and of others that failed during testing. There were very few statistical data that could be used to assess either reliability or failure rates for specific devices used in branch circuits. This is not too unexpected: there does not appear to be any agreed-upon life expectancy for such devices, and there is apparently no correlation between service requirements and testing procedures. In the absence of such correlation, the Canadian Standards Association and regulatory bodies in all other countries have adopted arbitrary performance requirements which accelerate contact failure and can be used to compare devices whether wired with copper or aluminum.

A description of a contact interface and of some specific degradation mechanisms follows.

a. The Contact Interface. The contact interface between two metals has been pictured as a volume containing atmospheric contaminants (such as carbon, chlorine, and sulphur), oxide films and oxide fragments, porosity, cold-worked grains, and small areas of metal-to-metal contact. The diameter of these areas is estimated to be in the range 1,000 to 10,000 Å.

The nominal temperature of the connection is governed by the current; conductor material, size, and insulation; ventilation; connector material, size, and radiating area; and also by the area of metal-to-metal contact between conductor and connector. Ideally the connection should operate at the same temperature as the conductor or at a lower temperature.

The supertemperature at the a-spots is controlled by the contact-voltage drop, which is determined by the current and the contact resistance. The resistance is a function of the contact material and the size of the a-spots for clean contacts, with a film resistance added for dirty contacts. With a large metal-to-metal contact area and with normal or rated currents, the contact should not overheat. With a small metal-to-metal contact area there will be a high contact resistance, and overheating and contact failure will result.

Two types of failures have been reported. The first kind resulted from low initial contact loads or torques which never created an adequate area of metal-to-metal contact. The second kind resulted from degradation of a-spots by electric, thermal, mechanical, and chemical effects. A description of these failure types and failure mechanisms follows.

b. Failure of Loose Contacts. In section 2.5.6 it has been shown that initially loose connections are prevalent in aluminum-wired devices. Copper and aluminum conductors can fail in a similar manner if the connection is initially loose. W.J. Meese et al. (NBSIR 75-672, 1975) have produced *glows* in laboratory tests with AWG-14 and -12 copper wire and AWG-12 and -10 aluminum wire attached to duplex receptacles with steel binding-head screws at torques of 2 lb-in. No glow could be developed when the screw was made from brass. From 5 to 35 watts of power could be dissipated at a glowing connection, and temperatures in excess of 400°C. could be reached in less than 10 minutes without blowing fuses or tripping circuit breakers. The glows could last over 100 hours, and could cause extensive charring of circuit components and adjacent materials. A laboratory fire has been started from a glow.

c. Failure of Tight Contacts. The second and more vexing problem of failure in tightly made connectors is illustrated by the work of E. Lassman (1941). He heat-cycled, 50 times between 15°C. and 120°C. for 30-minute periods, 2.5-mm^2 solid-aluminum and solid-copper conductors connected to looped-wire binding screws with the same controlled torque. The voltage drop across

the contacts was measured after each fifth cycle. Two copper and eight aluminum loops were tested. The voltage drop for copper-wire connections remained low throughout the test, while that for all eight aluminum connections increased to such high values in 30 to 35 cycles that the tests were discontinued. These results confirmed the well-known fact that wire binding-head screw connections can be reliably made to copper conductors. The unsatisfactory behaviour of the aluminum wire under the binding-head screw was explained by the fact that aluminum conductors underwent a further deformation after the screw was tightened. Because of this additional deformation, the pressure of the clamp on the conductor was not sufficient to maintain the minimum contact pressure required for a small voltage drop. Lassman considered that a spring was always necessary with an aluminum conductor to compensate for any cold flow, creep, or stress relaxation.

Tests on other connector types, including straight-wire binding screw, set screw, and pressure-bar clamp, confirmed that a spring could compensate for cold flow, creep, and stress relaxation of an aluminum conductor. These connectors not only performed well in heat-cycling tests when connected to aluminum, but the binding-screw and binding-post connectors also withstood severe vibration testing with no significant increase in contact-voltage drop.

The relevant German specification VDE 0281/1937 requires that aluminum conductors be scraped and coated with vaseline immediately prior to joining or clamping. R. Holm (1967) wrote that:

> When "permanent contacts" are constructed so that they do not breathe, their life is practically infinite. Richter and Schade (ETZ 59 (1938) 1321) observed that clamped aluminium contacts which were good the first year remained fit for use 20 years more, at least.

As reported previously, Holm also measured the contact resistance in binding-head screw connections to aluminum and copper wire at various torques and after ageing at 100°C. for times up to one year. He showed that contact resistance increased with the time of ageing — a relatively small amount in most cases — but extremely large increases (0.8 to 1600×10^{-4} Ω) were observed for aluminum-zinc contacts at low loads (90 N). Holm concluded that only at loads under 100 N was the contact really poor and that a screw contact to aluminum wire would perform satisfactorily for long periods at a contact load of 200 N unless the clamp ledge was zinc or cadmium (contact loads need to be about ten times higher on flat surfaces than on wires). Holm tested copper wires, loaded to 350 N, at 150°C. for one year and noted only a decrease in contact resistance. A 10% increase in resistance was observed in aluminum tested at a pressure of 50 N and at 150°C. Temperature cycling caused a larger increase in contact resistance than a steady state increase in temperature.

These investigations illustrate many important features of contact behaviour. They show that a binding-screw type of connection, which is satisfactory with copper wire, can fail with aluminum wire. They also show that in aluminum, contact degradation occurs more readily if the surface is not properly cleaned, if the contact load is low, if the contact is subject to temperature cycling, and if cold flow, creep, and stress relaxation occur in the conductor. They also demonstrate the deleterious effect of zinc and cadmium on an aluminum contact.

So far we have used the word *failure* to describe a glowing contact and a contact in which a high contact resistance and a high contact temperature developed on testing. There are other definitions and manifestations of failure to be considered.

d. General Failure Mechanisms. D.C. Hubbard et al. (1954) found that the contact resistance of copper-wired connections was relatively unchanged by heat cycling but that the resistance of some aluminum-wired connections increased significantly (see Table 29). They also reported that high current surges caused failure of aluminum-wired connections that had not been cleaned prior to joining. High current surges had no effect on aluminum conductors cleaned prior to joining or on copper conductors whether cleaned or not cleaned. The authors suggested that wire brushing resulted in a thin oxide film with oxide particles embedded in a work-hardened surface layer and that this combination formed larger a-spots.

F.E. Sanford and J.I. Fisher (1958) found that, if the clamping force, temperature, and resistance remained constant throughout the test period, no laboratory failures occurred in their

aluminum conductor connections. The contact temperature could not be measured directly but was deduced from the contact-voltage drop, which at 0.1 volt caused the aluminum to soften and at 0.27 volt caused the aluminum to melt. Contact deterioration was associated with a distorted sine wave of voltage, erratic voltage drops, and, finally, a rapid rise in voltage.

Table 29

EFFECT OF HEAT CYCLING OF CONTACT RESISTANCE
OF COPPER AND ALUMINUM CONDUCTORS

Compound	Torque, Inch-Pounds	Approximate Force, Pounds	Contact Resistance	
			Initial	Final
Copper				
No	50	600	240	295
No	100	1200	210	250
No	150	1800	180	210
No	200	2400	180	210
Yes	50	600	250	290
Yes	100	1200	210	240
Yes	150	1800	220	230
Aluminum				
No	50	600	575	1105
No	100	1200	280	290
No	150	1800	240	230
No	200	2400	230	230
Yes	50	600	380	1380
Yes	100	1200	320	400
Yes	150	1800	280	260

Commission's note: The resistance values are given in microhms.

Tests were made on AWG-4 solid-aluminum conductors clamped between flat plates 1 1/4 inch square and cycled 400 times at a current of 115 amperes for 1/2 hour on/off. The clamping force, contact resistance, and bulk-connector temperature were measured. Some results are shown in Figure 47.

Typical contact resistances ranged from 150 to 2,000 $\mu\Omega$, and temperatures from approximately 37°C. to 74°C. The high initial resistance of 2,000 $\mu\Omega$ in sample 1L3C resulted in an unstable connection with a high temperature and the largest relaxation of clamping force. The central role of Al_2O_3 and surface films in contact degradation is clearly indicated by the authors' observations that there were no failures in any test where the contact surfaces had been cleaned thoroughly before joining. It was necessary to anodize the contact surfaces to obtain the high resistances and temperatures associated with field failures.

Metallographic studies of failed contacts showed extensive damage and melting along the original contact interface. The test results showed that contact stability was essential to prevent the contact deterioration that is irreversible in aluminum, i.e., Al_2O_3 has a very high resistivity, is very stable, and does not dissolve in aluminum. Cuprous oxide (Cu_2O), on the other hand, is a semiconductor with a negative coefficient of resistance, which can dissolve in the copper metal when the temperature approaches half of the melting point.

The major factors that caused increases in contact resistance were temperature changes, mechanical disturbances, fault currents, and corrosion. These effects could be minimized by cleaning the aluminum surfaces prior to joining, using a joint compound, and applying a high clamping force. The connector also had to be massive enough to provide mechanical stability, to cause a low unit stress on the aluminum, to prevent excessive cold flow, creep, and stress relaxation, and to effectively dissipate heat. Connectors should be designed to also disrupt the oxide film on the aluminum.

K. Sato et al. (1976) used scanning-electron microscopy and electron-probe microanalyses to show that melting and transfer of contact material occurred at the interface during failure.

L. Roullier (1963) defined joint failure as that which occurs when the connector temperature rises above the conductor temperature, and believed that this happened when a sufficient number of a-spot contacts were broken and there was an increase in contact resistance. Little fundamental work has been done to determine the cause of failure but Roullier postulated that it could be caused by:
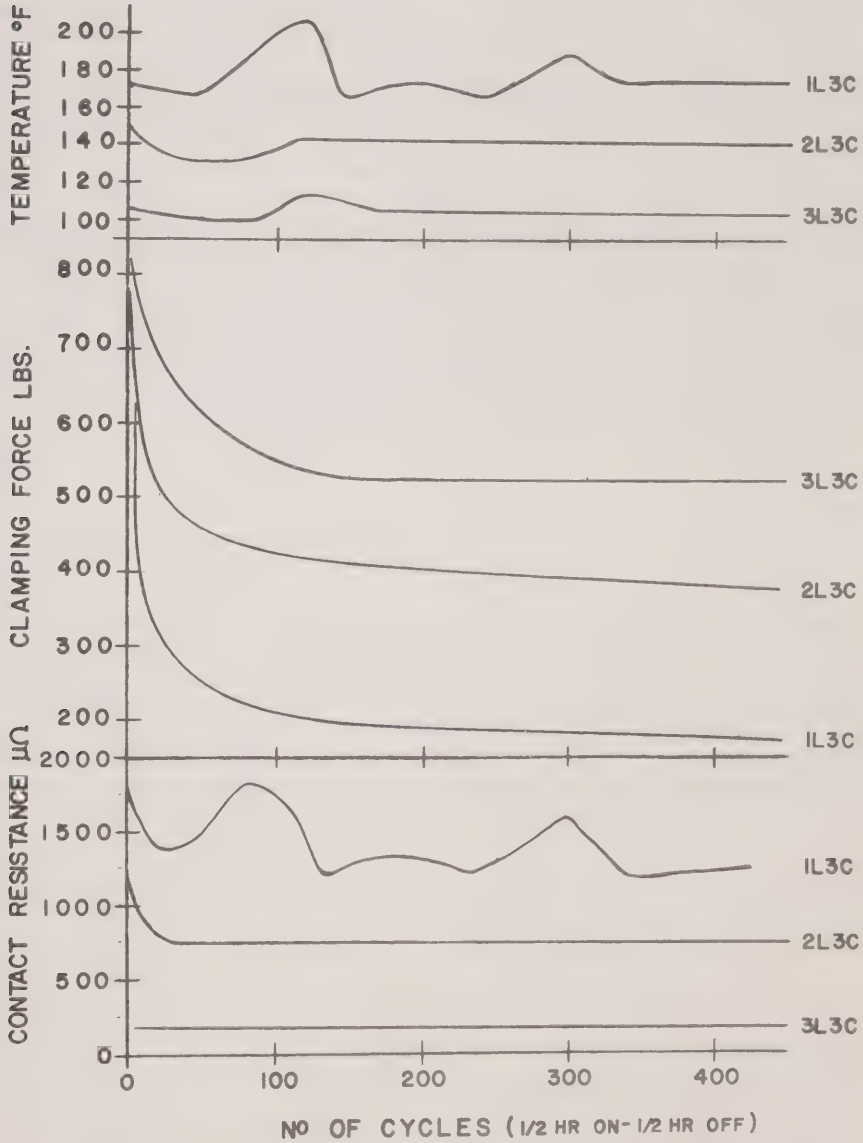
Figure 47.   Typical Test Results for Three Aluminum-Conductor Connections Showing the Relationships Among Contact Temperature, Contact Clamping Force, and Contact Resistance

1. Thermo-mechanical stresses at the contact region.
2. Differential strain recovery between conductor and connector. This is a function of the elastic modulus, hardness, and per-cent deformation of conductor and connector. If the connector has a greater spring-back than the conductor, the contact interface will be placed in tension and be more liable to failure.
3. Relaxation of interface pressure due to creep, differential thermal expansion, vibration, etc.
4. Oxidation of contact areas. The volume of Al_2O_3 is larger than the volume of metal from which it forms and this may exert a mechanical stress as well as chemically increase joint resistance.
5. Current loading. The current density in the contact area is a major factor in determining joint life.

Roullier (1967) outlined a failure sequence for a static contact interface in aluminum. He postulated that the metal-to-metal contacts formed at breaks in the oxide film conducted the current and caused a constriction of current and a constriction resistance. Melting of some a-spots occurred as the current density increased. These very small melted areas coalesced into a microscopically visible molten region at a later stage in contact deterioration. Arcing, along with further coalescence of molten zones, and overall heating of the contact occurred. Small, black arcing pits were now visible to the naked eye on the contact surface. The melting did not improve the joint by a welding action because the rate of heating spread the molten metal over a larger area and also the rapid cooling resulted in fracture. The initial deterioration of a-spots was attributed to mechanical failure of some of the weaker welds for reasons not yet completely understood. Roullier found it difficult to assess the significance of each of these mechanisms and he suggested that until more was known about basic failure mechanisms, tests which simulated the most rigorous service conditions must be used to evaluate connections.
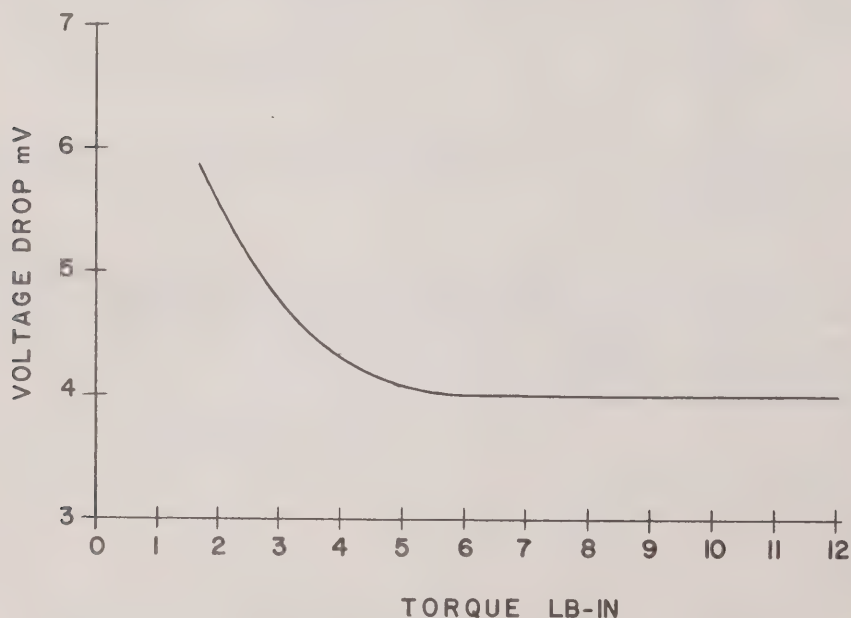
Figure 48.   Typical Torque-Resistance Curves for Standard Brass Terminals and 4-mm² (1/2 H) Solid-Aluminum Conductor

Voltage drop is measured across two barrel terminals and $3^1/_{16}$ inches of conductor.

Roullier is not alone in pleading ignorance about the failure mechanism. J.B.P. Williamson (1962), in discussing the question of which property of a joint determined its long-term behaviour, stated that a large voltage drop was associated with early failure for unknown reasons.

H. Halcro-Johnston (1968) studied the performance of 4-mm² half-hard aluminum conductors connected to conventional brass set-screw terminals, a type used in socket outlets and junction boxes in the United Kingdom. He considered that a-spot degradation could be caused by chemical (oxidation and corrosion), mechanical (creep or differential thermal expansion), or electric (heating) processes. Although electric overheating always appeared to be the cause of contact failure, he argued that if the contact were well-made initially, either chemical or mechanical factors must be responsible for breaking the a-spots, thus increasing contact resistance and contact temperature. Sufficient torque must be applied to establish a low-resistance electric connection. Figure 48 shows the torque-voltage drop relationship measured for this type of connection. The recommended tightening torque was 8½ lb-in.

A series of tests, in which the relative humidity was varied from ambient to 100%, resulted in no failures and appeared to rule out the chemical failure mechanism, leaving only the mechanical. The mechanical mechanism was investigated by current-cycling tests at 30 amperes for 5 hours on and 1 hour off, with results shown in Table 30.

Table 30

COMPARISON OF JOINT PERFORMANCE AT DIFFERENT TIGHTENING TORQUES

Type of Fitting	Tightening Torque lb-in	Conductor Lay	No. of Fittings	No. of Failures	% Failures	Total Time on Test Hours	Time to First Failure Hours
Socket outlet	6	Twisted	6	4	66.6	13,368	720
Socket outlet	6	Parallel	6	5	83.5	13,368	1240
Socket outlet	8.5	Parallel	6	0	–	13,368	.
Junction box	6	Parallel	12	12	100	3,220	270
Junction box	8.5	Parallel	6	3	50	13,368	8400

Commission's note: Tests were conducted with two 4-mm² half-hard conductors per brass set-screw terminal with a load current of 30 amperes for cycles of 5 hours on and 1 hour off.

There was a striking improvement in performance at the higher torque. However, the only connection with no failures was the socket outlet where the set screw at the higher torque contacted both aluminum conductors. The junction-box connectors, in which the aluminum conductors simply rubbed together, was not considered to be a suitable connector, particularly if three wires had to be joined. All three wired terminals tested failed after very short testing times.

As a result of these tests, Halcro-Johnston recommended the use of proper tightening torques, the joining of no more than two aluminum wires in a single connection, and the use of only those accessories with terminals suitable for connecting solid-aluminum conductors. To meet this last requirement he suggested,

a type approval testing specification be agreed upon for accessories to be used with aluminium conductors. This should take the form of a life test under load cycling conditions. . . . The current should be set above the rating of the cable to provide the required degree of acceleration. The duration of the test and the number of samples to be tested are obviously matters to be agreed upon amongst accessory manufacturers.

R.D. Naybour and T. Farrell (1973) evaluated contact stability of simple butt joints in EC-grade aluminum, and concluded that an aluminum interface could be made stable if rough surfaces were loaded and maintained above 1,000 N, that stress relaxation would not be a problem at temperatures up to 125°C. if the bulk stress was less than 60 N/mm², and that normal current loadings did not cause contact degradation. Their research showed that both surface roughness and abrasion of the aluminum just prior to connection had a significant effect on the resulting contact resistance. A rough surface (2.5 μm C.L.A.), freshly abraded and then connected at loads near the 0.1% proof stress, had a resistance of ~20 μΩ compared to ~90 μΩ in a sample abraded 30 days before connecting. For smooth surfaces (0.06 μm C.L.A.) in annealed aluminum, the joint resistances were appreciably higher as shown in the following tabulation:

Load (Newtons)	Resistance ($\mu\Omega$)
~1,000	~4,800
~2,000	~4,200
~2,200	~1,900
~3,500	~900

Also, with smooth surfaces, an anomalous decrease in resistance occurred as the load relaxed. The decrease was attributed to an interface shear which created new areas of metal-to-metal contact. It also demonstrated the important role that contact geometry could play in connector performance. The contact resistance of smooth surfaces could be reduced to the same value as that of rough surfaces by 10% plastic deformation, but this required a load of 5,000 N. The same (10 to 12 $\mu\Omega$) resistance required a force of only 2,500 N for freshly prepared rough surfaces. In a work-hardened sample of aluminum, a load of 2,500 N resulted in a joint resistance of 3,000 $\mu\Omega$.

Mechanical load-cycling tests were conducted in the flat portion of Figure 48, in this case, at loads between 1,000 and 2,500 N. In this region there was no acceleration in contact degradation after hundreds of test cycles.

At the aluminum wiring meeting, convened by Consumer Product Safety Commission in Washington, D.C., on August 5, 1974, W.H. Abbott, from Battelle Columbus Laboratories, in Columbus, Ohio, discussed failure mechanisms in both aluminum- and copper-wired devices. He argued convincingly that neither copper nor aluminum contacts would fail unless there was mechanical motion between the conductor and the connector. Poor workmanship (i.e., loose connections) was responsible for some failures and an increase in torque from 6 to 9 lb-in could increase the projected failure time of a binding-head screw device from tens of months to tens of years. "Torque has a fantastic effect." Failures also occurred in binding-screw connections that were initially tight. These failures were critically dependent on the operating temperature and the number of current or heating cycles, and they obeyed an Arrhenius type of rate law. It was almost impossible to produce failure at constant temperature. A high resistance at the break-off tab could raise the operating temperature in duplex receptacles, and a 10°C. rise in temperature could produce a 100-to-1 difference in cyclic life.

Fretting-corrosion failures did occur and were characterized by the presence of very small black spots on the contact interface when the connection was dismantled. A metallographic cross section showed a relatively thick, compacted oxide film at the contact interface. Microscopic fretting motion at the interface could result from short-range differential thermal-expansion effects. These might not be translated into the bulk where they could be measured. However, Abbott also stated that copper could withstand cyclic wear better than aluminum by a ratio of 5 or 10 to 1.

Indium diffusion did take place but with no measurable effect on contact resistance. There was, however, a reduced tolerance to fretting-corrosion damage of both aluminum and copper.

The effects of high transient currents have not been evaluated.

e. *Specific Contact-Failure Mechanisms*

(i) Differential Thermal Expansion. Variations in electric loads result in temperature fluctuations in conductors and connectors in addition to variations caused by changes in the ambient temperature. Relative motion of small magnitude is to be expected because of differences in thermal expansion of dissimilar metals.

Differential thermal expansion is the most commonly accepted explanation for relative motion between aluminum and brass or other metal at a contact interface. If this motion is large enough, a-spots can be broken and contact resistance and contact temperature can increase. The prevailing opinion is that failure would take a very long time to occur, even at an elevated temperature, if that temperature was constant. Temperature cycling — which causes flow, creep, and stress relaxation in the aluminum — is believed to accelerate the failure process by lowering the contact pressure, while vibration, mechanical disturbance, and differential thermal expansion fracture the a-spots and allow a high-resistance oxide film to form. Repeated relative motion at the contact surfaces can cause a fretting-corrosion type of failure.

The relative motion is longitudinal as well as radial with respect to the centre of the conductor. It is likely that most motion occurs at a-spots where contact resistance and current density are high and, therefore, heating and expansion are also high. J.B.P. Williamson (1964) stated

that displacement of contact spots allowed oxide to form and, when cooling occurred and the spots returned to their original location, the electric contact was lost.

This type of deterioration is progressive, with contact resistance rising with each heat cycle and correspondingly higher temperatures resulting in an increased rate of contact degradation. At higher temperatures creep and stress relaxation also occur more rapidly, with a further incremental lowering of contact pressure and a rise in contact resistance and temperature. The rate of heat-cycling deterioration increases with time and will cause final, rapid joint failure.

E.R. Wallach and G.J. Davies (1977) estimated the elastic strains generated at an aluminum-copper interface and showed that these were sufficient to cause plastic deformation or shearing along the interface of the weaker aluminum. Both heating and cooling resulted in differential thermal motion but, in the case of an aluminum wire in a copper connector, the higher coefficient of expansion of aluminum resulted in a tighter connection and, if the temperature rise was large enough, the aluminum was plastically deformed. On cooling the connection, each metal contracted by an amount $d\varepsilon$ given by:

$$d\varepsilon = \alpha \Delta T$$

where

$$\alpha = \text{coefficient of thermal expansion}$$
$$\Delta T = \text{temperature change}$$

The differential strain between copper and aluminum would thus be:

$$d\varepsilon = \Delta T[\alpha(Al) - \alpha(Cu)]$$
$$\alpha(Al) = 24.0 \times 10^{-6}/°C$$
$$\alpha(Cu) = 17.2 \times 10^{-6}/°C$$

If ΔT is assumed to be 200°C., then $d\varepsilon = 13.6 \times 10^{-4}$.

The yield stress of pure aluminum is $\sim$30 MN/m^2 and the modulus (E) of aluminum is $\sim$70.6 GN/m^2. Therefore, the yield strain ε_y is approximately 4.2×10^{-4}. Thus the aluminum should yield when the connection is cooled. Calculations show that a temperature change of 62°C. is sufficient to exceed the yield strain of aluminum. For aluminum in contact with steel, a temperature change of 40°C. exceeds the yield strain in aluminum.

Aluminum in a stronger copper connector will expand when heated and will flow out of the contact area when the yield stress is exceeded. When cooled, the copper returns to its original dimensions while the aluminum is smaller by the amount of plastic flow and the contact force, therefore, is reduced. If a few a-spots are fractured, the joint resistance increases very slightly and only a slight rise in contact temperature occurs. If the fracture of a-spots continues with further thermal cycles, an increase in contact temperature will occur. When fracture of the last few (10 to 20) a-spots begins, there will be a runaway condition at the connection.

This process, which has also been described as *thermal ratcheting*, can occur in a binding-head screw connection as the increase in temperature causes the lower-strength aluminum conductor to flow plastically and to extrude from under the stronger brass or steel binding-head screw. The aluminum wire is now distorted and cooling causes it to contract more than the screw, thus loosening the connection. Heating and cooling cycles, or thermal ratcheting, if continued, can lead to a fretting-corrosion failure of the connection.

(ii) Oxidation. The experimental evidence confirms that the presence of a thick oxide film in both aluminum and copper results in high contact resistance and an unstable joint with erratic fluctuations in contact voltage and temperature. The problem appears to be more serious in aluminum because of the stability and high resistance of the insulating oxide film, contrasted with a much lower resistivity with a negative temperature coefficient for cuprous oxide. This oxide (Cu_2O) can also dissolve in copper at elevated temperatures and thus lower joint resistance.

It has been shown that the oxide film must be broken to establish metal-to-metal conducting contacts and it has also been suggested that oxidation of these small contacts could be a cause

of connector failures. R.S. Timsit (1977) showed that, at a temperature of 100°C., oxidation could not lead to a-spot failures because aluminum oxide at this temperature reached a low and limiting thickness which would not appreciably reduce the diameter of the conducting a-spots. E. Takano and K. Mano (1968) showed that simple reduction of a-spot diameter by progressive oxidation was feasible in copper contacts.

(iii) Current Overload and Short Circuits. Although it is generally accepted that the contact will not fail unless there is mechanical motion at the interface, there is evidence that a short-circuit current can cause contact degradation at improperly cleaned surfaces in aluminum. The Copper Development Association Inc. Newsletter, dated March 28, 1974, stated that overloads would not loosen copper joints; that current surges could harm a wiring system, and that copper, of all wiring materials, was best able to withstand overloads. A faulty copper connection could heal itself since the copper oxide was reasonably conductive and since the current flow through a connection could puncture the film-thick gap and cause arcing and spot welding over a wide range of currents. The insulating properties of Al_2O_3 precluded this type of action. This aspect of aluminum-contact deterioration is not evaluated by current testing procedures.

(iv) Creep. There is a great deal of published data that show that for equivalent stresses and temperatures EC-grade aluminum creeps more rapidly than copper or aluminum alloys. This is
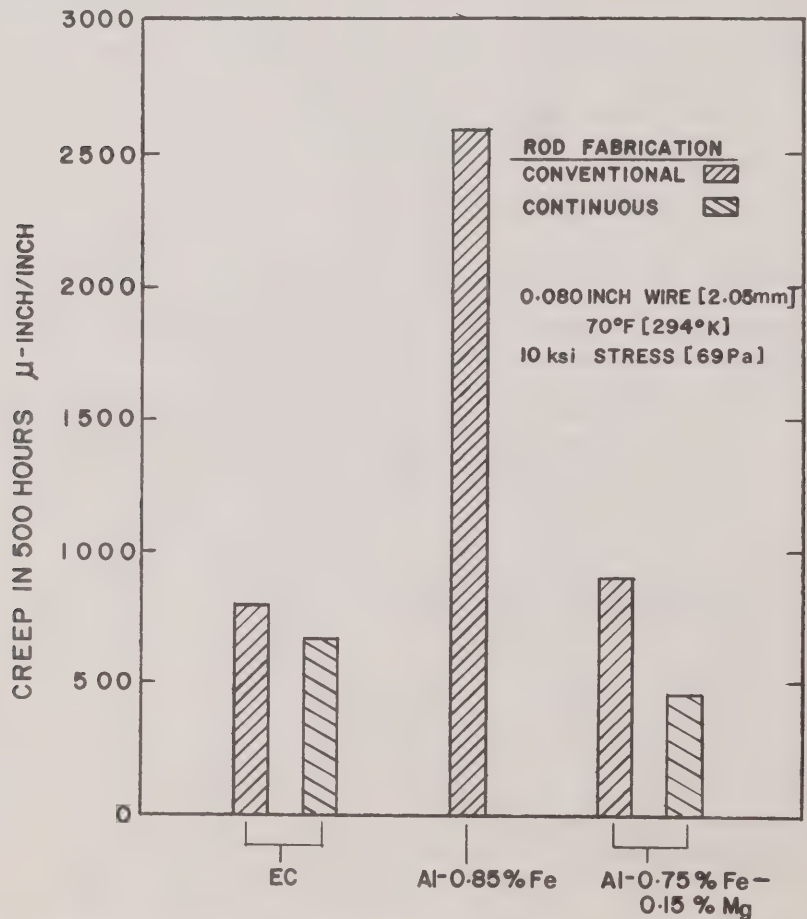
Figure 49. Room-Temperature Tensile Creep in 500 Hours of H19 Temper Wire of Several Alloys

said to result in lowering of contact forces and increasing of contact resistance and tempera-ture. The superior contact performance of the more creep-resistant aluminum alloys which have been developed recently supports this contention.

R.W. Westerlund (1974) measured the creep of conventionally and continuously fabricated EC-aluminum, iron-aluminum, and iron-magnesium-aluminum alloys, as shown in Figure 49. He also showed that changes in contact resistance and creep parallelled each other and that changes in resistance and strength could be brought about by differing annealing treatments, as shown in Table 31.

Table 31

STRAIN AGEING EFFECTS IN AL-0.75% FE-0.15% MG ALLOY WIRE
(CONVENTIONAL ROD FABRICATION)

Annealing Treatment	Tensile Strength		Yield Strength		Elongation % in 10 in.	Conductivity % IACS	ρ $\mu\Omega$-cm	Strain Ageing Effect
	ksi	mPa	ksi	mPa				
1 min/900°F.	18.3	(126)	8.4	58	24	59.6	2.90	Mild
1 h/600°F.	18.3	(126)	10.7	74	22	60.6	2.84	Very slight
16 h/500°F.	18.8	(130)	12.7	88	18	61.3	2.81	None

Since the annealing treatments changed the amount of solute in solution, the changes in creep strength and resistance were attributed to the segregation of solute to dislocations. The strain-ageing phenomenon reported supported that mechanism. Specifically, the resistance to both an-nealing and creep was significantly reduced by adding 0.65% iron to an EC-aluminum alloy. There is no real explanation of the effect. However, an increase in precipitated particles was observed with iron and with other sparingly soluble elements, which suggested that insoluble intermetallic phases had similar effects on creep resistance. The resistance to both annealing and creep was significantly increased by adding 0.15% magnesium to an EC-aluminum alloy.

There appear to be no direct experimental measurements that prove that creep alone can result in contact failure. In fact, the measurements of K. Sato et al. (1976), given in Figure 50, showed that the tensile creep of EC-grade aluminum in the hard condition was very much less than that of EC-grade aluminum in the annealed condition and yet the reported contact-failure rate of EC-hard-grade aluminum was unacceptably high in binding-head screw connections. Also it is difficult to associate the excellent contact behaviour of copper-clad aluminum with any significant increase in creep strength. Differing physical and chemical properties of the copper and aluminum surfaces appear to be the major factors.

(v) Stress Relaxation. Stress relaxation is the time-dependent reduction in stress that can occur at constant strain and temperature, and is due to the conversion of elastic to plastic strain. The amount of stress relaxation that occurs in a given circumstance is dependent on the particular alloy used and its processing history, the stress level, and the temperature. Thus, we see that the rate of stress relaxation depends on the stress level, while the contact resistance depends on the applied load or force. As will be shown, aluminum has a higher rate of stress relaxation than copper for equivalent stresses and, to equalize this factor, it is necessary to reduce the stress on aluminum by using a larger area of connector contact.

The exact position and shape of the contact-resistance, contact-force curve are a complex function of the type of conductor and connector used, of the surface roughness and surface preparation techniques, of the load and stress applied, and of the temperature. This is an area of intense research by many specialized connector manufacturers and by research laboratories throughout the world. Each individual connection presents a spectrum of problems which, in general, must be solved empirically to produce, economically, a connection with a low-contact resistance. Thus, even in the 1970's, in fields where aluminum and copper have been used for many decades, connection problems still arise and many different solutions are found. One solution, suggested by R. Attermo (1973), was to improve oxidation, creep resistance, and
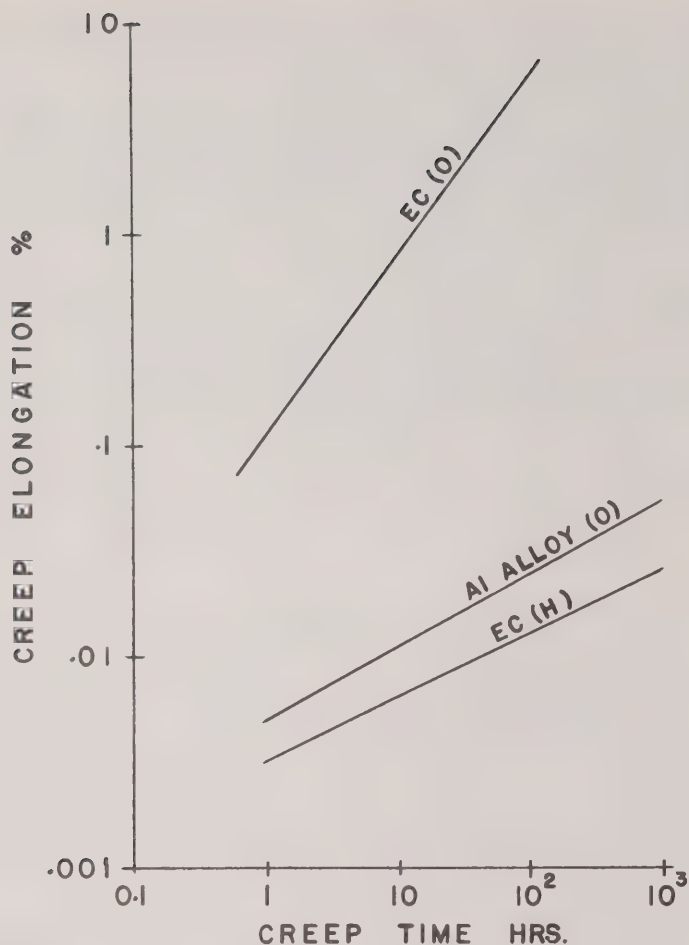
Figure 50.   Tensile-Creep Properties of Aluminum and Aluminum Alloys
at Room Temperature

stress-relaxation behaviour in relation to EC-grade aluminum conductors. The desired im-
provements could be obtained by (1) plating, (2) alloying, (3) creating better designs for con-
nectors. For example:

1. Copper-clad and nickel-clad (Sinipal) conductors have been developed by Texas Instru-
    ments, U.S.A., and by Sieverts Kabelverk AB, Sweden, respectively. Copper cladding
    prevents the formation of aluminum oxide and appears to perform in connections nearly
    as well as solid copper. Nickel-plated aluminum appears to be comparable to copper-
    clad aluminum, but is said to be lower in cost than copper, copper-clad aluminum, and
    the newer aluminum alloys listed by the Underwriters' Laboratories, Inc. in the United
    States.

2. Wiring manufacturers throughout the world have developed many new aluminum alloys
    which have better strength, ductility, and stress-relaxation behaviour than EC-grade
    aluminum.

3. Connectors could be designed with suitable springs to maintain contact pressure, thus
    preventing stress relaxation, or joints could be made by soldering or welding techniques
    that require no residual stress for contact stability. Compression bonding or cold
    welding is particularly suitable for aluminum, but suitable tools and techniques for

branch circuits have not yet been developed. The National Bureau of Standards in the United States is presently engaged in such developments.

In laboratory tests I. Matthysse (1951) compared the performance of identical connectors, maintained at an initial torque of 300 lb-in by retightening, with those allowed to relax. No significant difference in contact resistance or temperature was observed.

C.G. Sorflaten (1960) measured creep and relaxation of 13% to 16% of the initial load and concluded that, if the clamping force was reduced by less than 20% of the optimum value on heating for 1 hour at 100°C., good service behaviour could be expected. He considered that corrosion would not be a serious problem in aluminum building wires; that the contact resistance could be lowered and extra corrosion protection obtained by using a tin-plated connector; that differential thermal expansion should not be a problem in the lower current ranges (30 to 70 amperes); and that steel set screws could be used with aluminum terminals in this region. Elastic spring-back might be a problem.

R.D. Naybour and T. Farrell (1973) showed that, for electric-grade aluminum, the stress relaxation was higher at higher temperatures and larger initial stresses, and was higher for work-hardened than for annealed aluminum. They concluded that, if the initial stress was below 60 N/mm^2 at room temperature and the initial load was 2,000 N, failure of aluminum contacts due to stress relaxation was unlikely. An initial stress of 60 N/mm^2 at room temperature relaxed to one half in one year at 125°C. or 25 years at 80°C.

R. Attermo (1973) obtained data on compressive-stress relaxation for a variety of aluminum and copper conductors in sizes used in branch circuits, as shown in Figures 51 and 52. These data confirmed that the newer aluminum alloys with magnesium and iron additions had increased resistance to stress relaxation over EC-grade aluminum, as well as greater strength and elongation. Increasing the temperature and the amount of work hardening augmented the rate of stress relaxation.
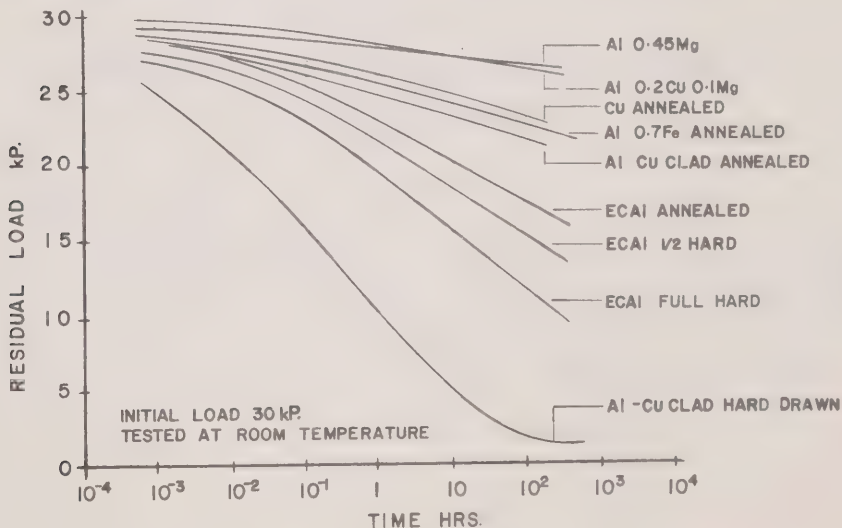
Figure 51.   Relaxation Curves from Test at Room Temperature

The effect of work hardening on stress relaxation was particularly pronounced in the case of copper-clad aluminum, and S. Schlosser et al. (1973) reported 25 contact failures in hard, copper-clad aluminum conductors in a 3,000-hour cyclic-loading test, with no failures when the wires were annealed.

R. Attermo and R. Lagneborg (1974) demonstrated that stress relaxation in hard-drawn EC-grade aluminum conductors was anisotropic, being much faster in the transverse than in the longitudinal direction, and much faster in hard-drawn wire than in annealed wire. Table 32 shows that there was little or no anisotropy in stress relaxation in annealed EC-grade

aluminum. Attermo and Lagneborg also showed that a heat treatment at 280°C. for 7 minutes for hard-drawn aluminum decreased the stress relaxation to the same values as those for annealed wires. This suggested that a Bauschinger effect was responsible for the observed differences.
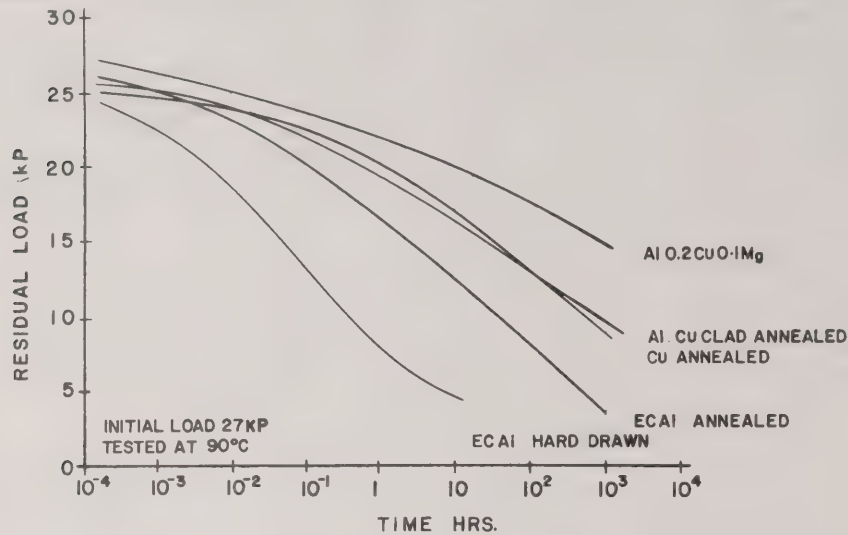
Figure 52.   Relaxation Curves from Test at 90°C. (190°F.)

Table 32

STRESS RELAXATION IN HARD-DRAWN EC ALUMINUM

Direction	Residual Stress MN/m^2		
	10^{-4} Hour	1 Hour	10^2 Hours
Longitudinal	150 HD*	130	120
Transverse	150 HD	100	75
Longitudinal	80 A**	76	75
Transverse	80 A	78	75
Longitudinal	80 HD	77	75
Transverse	80 HD	76	45
Longitudinal	50 A	—	—
Transverse	50 A	45	43
Longitudinal	50 HD	47	45
Transverse	50 HD	40	25

*HD is hard-drawn aluminum
**A is annealed aluminum

K. Sato et al. (1976) measured the compressive relaxation that occurred in annealed copper and annealed EC-grade aluminum, annealed aluminum-alloy material, and half- and full-hard EC-grade aluminum at room temperature and 100°C. Figures 53 and 54 show that copper relaxed less than EC-grade aluminum of any temper, and less than the aluminum-alloy material. At room temperature the annealed copper was only marginally better than the annealed aluminum alloy and the EC-grade aluminum became progressively poorer as the hard-

ness intensified. Raising the temperature increased the amount of relaxation. Sato et al. considered that for uncoated aluminum conductors compressive-stress relaxation was the most important factor in assuring good electric connectability, and that in this respect the aluminum-alloy material was best and full-hard EC-grade aluminum worst. Copper was superior to uncoated- and coated-aluminum conductors on the basis of temperature increase at the joint.
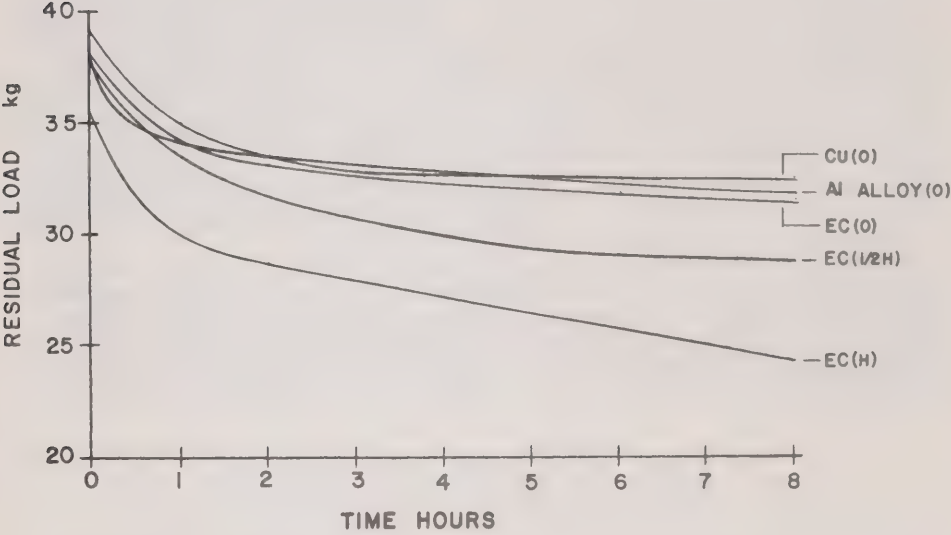
Figure 53.   Relaxation Properties of Various Conductors at Room Temperature
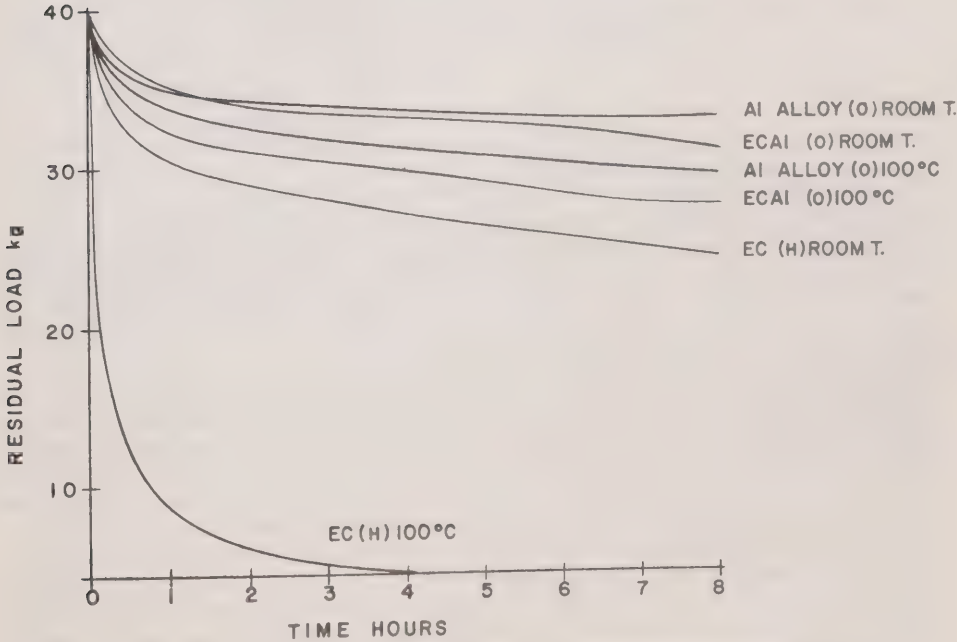
Figure 54.   Relaxation Properties of Various Alloys at 100°C.

It is most difficult to assess the quantitative importance of stress relaxation in contact failure because the basic contact-force, contact-resistance curves show that there is no significant increase in resistance until the contact force drops to a very low value. There is no doubt, however, that if a connection loosens because of relaxation the a-spots can be much more easily ruptured by vibration or other mechanical disturbances.

(vi) Fretting Corrosion. The process known as fretting corrosion occurs when very small relative movements between two mating surfaces cause surface damage and oxidation if the surfaces react with the environment. In electric contacts the small relative motion at the contact surfaces not only can deform and fracture a-spots but also can generate oxide debris and alter the surface topography, hardness, and chemical composition. Oxidation is increased because the relative motion exposes virgin metal to the atmosphere and the changes in physical and mechanical properties of the surface layer occur because of the introduction of deformation-induced defects. All these processes will increase both metal and film resistivity, joint resistance, and joint temperature. In branch circuits wired with aluminum and connected to brass, copper, or steel, it has been estimated that the relative motion resulting from differential thermal expansion and contraction could cause fretting failures.

The small amount of motion and the production of oxide debris are characteristics of fretting corrosion and distinguish it from normal wear. G.A. Tomlinson et al. (1939) showed that slip between the surfaces was necessary for fretting but the actual amount of slip required could be as little as $\pm 0.5 \times 10^{-7}$ inch. W.P. Mason and S.D. White (1952) determined that the critical amplitude for fretting corrosion for spherical rubbing surfaces obeyed the following relationship:

$$d = \frac{\left(\frac{3W}{G}\right)^{2/3}(2-\gamma)f}{8\sqrt[3]{r(1-\gamma)}}\left[1 - \left(1 - \frac{T}{fG}\right)^{2/3}\right] \tag{29}$$

where

$$
\begin{aligned}
d &= \text{critical displacement for slip} \\
W &= \text{normal load} \\
G &= \text{shear modulus} \\
\gamma &= \text{Poisson's ratio} \\
r &= \text{radius of curvature of surface(s)} \\
f &= \text{coefficient of friction} \\
T &= \text{tangential load}
\end{aligned}
$$

and determined a critical amplitude for fretting corrosion of 7.5×10^{-5} cm.

Tomlinson also showed that there could be purely elastic relative motion (no slip) of 20×10^{-6} inches and no fretting corrosion resulted. He postulated a very high elastic shear of the surface material. Also, in the sphere on flat experiments, the tangential displacement was mostly elastic from $\pm 2 \times 10^{-5}$ inches but about $\pm 2.6 \times 10^{-6}$ inches of slip allowed fretting corrosion to occur. Normal pressures between 3 and 26 tons per square inch did not affect stress corrosion nor did test speed between 100 and 400 alterations per minute.

E.M. Bock and J.H. Whitley (1974) showed that all non-noble metals were susceptible to some degree of fretting corrosion, which produced an increase in contact resistance. Boundary lubricants were beneficial but did not eliminate damage. The authors warned that any electric contacts of non-noble metals subjected to vibration, mechanical motion, or differential thermal expansion were subject to increased contact resistance through fretting corrosion. Trapped wear debris was believed responsible for the increase in constriction resistance.

H.H. Uhlig (1954) believed that fretting corrosion involved a chemical and a mechanical factor. Thus, an asperity ploughed a track that oxidized or adsorbed gas rapidly. The next asperity wipe initiated the reaction of adsorbed gas to form oxide and was the chemical factor in fretting corrosion. Asperities caused wear by ploughing and by welding and shearing, and there was a secondary fretting action caused by the interaction of debris; these are the mechanical

factors. In the chemical factor, he found an extremely wide variation of from 6% to 78% of the observed fretting-corrosion damage. At low loads, small slip, and low frequency, the chemical factor usually predominated while at high frequency mechanical wear was more important. Uhlig also found that aluminum and stainless steels were especially damaged by fretting corrosion because of the hard oxide particles and the rapidity with which both metals oxidized when exposed to air. This means that the chemical factor was more important for these metals, which have a high affinity for oxygen, than for the noble metals (e.g., gold, platinum) where damage must be largely mechanical.

J.H. Whitley (1976) found that fretting corrosion due to differential thermal expansion, vibration, and mechanical shock in a push-in type of module caused a 1-$\mu\Omega$ contact resistance to increase to more than $10\ \Omega$ in 1 hour. Small black spots at the male-female contact points were the clue that instigated an investigation of fretting corrosion. In fretting corrosion, the a-spots were fractured and oxides formed and remained in the contact area, producing a high contact resistance (e.g., in 20 to 30 minutes, the resistance could rise from $\sim 1\ \mu\Omega$ to $10{,}000\ \mu\Omega$ in unlubricated contacts). Mineral oil was effective in maintaining a low resistance. Whitley described the erratic nature of the failures as follows:

> *Fretting causes some contacts to fail, others not.* Fretting produces oxide film debris in the contact interface. In low voltage or dry circuit applications these films may have profound effects, while in power circuits they may be broken electrically without any detrimental effects on the circuit. Even in some low voltage circuit applications the contact resistance can reach very high values before equipment failure occurs. In our first encounter with the fretting problem only certain contacts in the system were identified as failures although all the contacts suffered from fretting to about the same extent. We later learned that the failing contacts were those in sensitive dry circuit positions in the equipment.

Whitley concluded that:
1. Fretting corrosion occurred with all non-noble metal contacts.
2. Contact force had no significant effect on fretting unless it prevented motion.
3. Lubrication could be effective in reducing fretting but effectiveness varied with the type of lubricant.
4. Cyclic motions of 2 μm could cause fretting in contacts.
5. Oxygen alone was required in fretting corrosion.

He believed that differential thermal expansion was the most important source of fretting motion, and proposed three methods of reducing fretting corrosion:
1. Use of noble-metal platings.
2. Prevention of motion.
3. Use of appropriate contact lubricant.

K.H.R. Wright (1952) showed that there was a transition temperature — which was independent of frequency and load — for copper, with a good surface finish, at 323°K. and for steel at 413°K., at which the wear resistance suddenly increased. Wright found that wear resistance above the critical temperature obeyed an Arrhenius equation. Battelle Columbus Laboratories has reported that contact failures in aluminum-wired devices also obeyed an Arrhenius law. Fretting corrosion, as well as creep and stress relaxation, should be considered as a rate-controlling step in the failure process.

M. Braunovic (1977) studied fretting corrosion of AWG-12 aluminum wire in contact with tin, silver, cadmium, zinc, and nickel. Contact loads of 10, 100, and 500 grams and motion of ±10 μm were used. All combinations were susceptible to fretting corrosion at 20-gram load, and voltage fluctuations began immediately in the aluminum-zinc combination. At 500-gram load, cadmium, zinc, and nickel (hard) showed no fretting corrosion with aluminum while silver, tin, and nickel (soft) still showed fretting damage. Scanning-electron microscope studies showed that both plating materials and wires were damaged and that large amounts of aluminum were transferred to both the tin- and the zinc-plated materials.

Braunovic concluded that initially there was good electric contact at welded asperities but fretting displacements ruptured these microscopic bridges and formed metallic and oxidized wear fragments. Contact was still good because the metallic debris was conducting. These regions progressively oxidized and reduced the real area of contact. In the second stage, work softening at asperities and oxidation occurred, with progressive separation, until metallic contact was destroyed.

(vii) Intermetallics and Diffusion Effects. Intermetallics are formed by diffusion and chemical reaction of metals that are in contact. Both copper and aluminum form intermetallic compounds with many other metals used in branch-circuit connections. In general, these compounds grow quickly only at high temperatures where diffusion is rapid. A high temperature for a metal is defined in terms of its melting point and is generally 0.3 to 0.5 of the melting temperature. Thus, for a metal like indium, with a melting point of 155°C., room temperature is a *high temperature*.

Both R.S. Timsit (1977) and M. Léger (1978) have presented data to show that, for a properly functioning and ideally static branch-circuit connection operating at a low temperature, an aluminum-copper intermetallic layer thick enough to significantly raise the contact resistance could not form in any reasonable length of time. In these calculations, only the volume diffusion of copper and aluminum forming intermetallics was considered. Grain-boundary diffusion and such surface effects as the vacancy-enhanced diffusion described by M. Braunovic (1977) were ignored. Braunovic studied the effect of thermal cycling on the surface and bulk properties of very pure (99.999%) aluminum and an aluminum-0.5% magnesium alloy. He postulated that thermal cycling generated vacancies at the oxide-metal interface and that these diffused inwards, giving a net flux of solute towards the surface. If this mechanism operated, it could lead to changes in resistivity of both the metal and the oxide at the contact surface and to a corresponding variation in contact resistance and temperature.

Both Léger and Timsit agreed that the mechanical properties of the joint could be affected adversely by very thin layers of intermetallics which could form. R.W. Barnard (1974) described the reactions of indium with copper and nickel. E.R. Wallach and G.J. Davies (1977) showed that copper-aluminum compounds could form. K.C. Lin and C.L. Carlson (1974) and C.L. Carlson and R.M. Leedy (1955) showed that the formation of a compound layer 0.0023 mm.-thick — primarily by diffusion of copper into aluminum — completely embrittled the joint. No embrittlement was predicted after 20 years at 80°C. but embrittlement occurred in 24 hours or less at 250°C. W.H. Abbott (1974) and others have pointed out that fretting damage was aggravated by the presence of intermetallics. U. Lindborg et al. (1975) showed that a 5-μm-thick tin coating is 70% to 80% converted to copper-tin intermetallics in seven years at 50°C. There is also a low-temperature allotropic transformation in tin.

It is clear that diffusion of solute can occur in electric contacts but the temperature dependence of the process and the role of mechanical and electric stresses at low temperatures have not been completely evaluated.

The dezincification of brass and the deposition of zinc on the base plate of a failed CO/ALR receptacle, which was examined by M. Léger (Ontario Hydro Research Division Report 78-54-K, dated February 2, 1978), and a similar phenomenon reported in the Aluminum Company of Canada, Ltd. Research Centre report (KR-78/006, dated January 19, 1978) have yet to be completely explained. Léger considered that arcing was a possibility.

(viii) Corrosion. There is evidence that corrosion does occur to a limited extent in branch-circuit connections. R. Patterson, of Canadian General Electric Limited, testified at a Commission hearing that rusting on the back steel support of some receptacles had been noted as well as shorting between the conductor and this back support. The corrosion products could cause a high resistance and arcing at the contact interface, and this could aggravate any mechanical damage caused by relative motion of the contact surfaces. D.C. Hubbard et al. (1954) reported that zinc was an unsatisfactory contact material because it did not maintain low resistivity and was attacked by both copper and aluminum in corrosive areas, producing a large volume of corrosive by-products.

f. *Summary of Connection Failures.* The literature reviewed contains a great deal of speculation, and a small amount of experimental evidence, on the basic mechanisms that cause failures in aluminum and copper electric connections in general and in residential branch circuits in particular. The factors that can cause failures in aluminum connections — as reported in the literature — are summarized in Table 33.

It appears that a large proportion — perhaps half of the failures in branch-circuit connections — can be attributed to initially loose connections. Loosening can result from failure to apply adequate torque, wire disturbance, improper wire looping, low torque in twist-on connectors, backwired receptacles, and, in some duplex receptacles, more contact motion when the break-off tab is removed.

W.H. Abbott (1974) indicated that, in a binding-head screw, an increase of torque from 6 to 9 lb-in could increase the cyclic-life expectancy from tens of months to tens of years. Thus, tight connections may be expected to perform satisfactorily and the major problem is to explain how "nominally" tight connections can loosen and cause overheating, or how overheating can cause loose connections, since it is evident that there will be synergistic effects among many of the proposed mechanisms.

Although, in general, mechanical motion is required to break a-spots, there are many reports of aluminum contacts, which had not been properly cleaned before being connected, being damaged by short-circuit currents. A damaged contact will operate at a higher temperature and hence have a shorter life. Differential thermal expansion is commonly accepted as being responsible for relative motion at contacting surfaces of dissimilar metals. The excellent contact performance of an aluminum conductor in an aluminum connector or in contact with an aluminum set screw is attributed to the absence of relative motion. The poor contact performance of aluminum conductors in brass or copper connectors or in contact with steel binding screws is attributed to excessive relative motion. If a sufficiently large increase in temperature occurs, an aluminum conductor in a brass connector can change shape by cold flow and creep. Stress relaxation can also occur, further loosening the connection. If the contact force becomes sufficiently low, additional temperature fluctuations, vibration, or other mechanical disturbances can fracture a-spots, thus increasing contact resistance and temperature and the rate of contact deterioration. In the final stages of failure, when few a-spots remain, there will be arcing and melting at the contact surfaces.

It has been stated that in a tight, well-made copper-aluminum connection, copper-aluminum intermetallic compounds will not form in sufficient thickness to increase appreciably the contact resistance. Yet there is no doubt that such compounds have been observed in failed receptacles. It is certain that diffusion can occur very rapidly even at room temperature in branch-circuit devices that have been plated with metals having a low melting point, such as indium and tin. The effect of such diffusion on electric and connectability behaviour has yet to be completely assessed. There is evidence that the connection does become brittle in the presence of a very thin layer of intermetallics and that damage caused by fretting corrosion is accelerated. The Canadian Electrical Association and Alcan are currently exploring this problem in more detail.

The newly developed ACM grade of aluminum-alloy conductors has lower creep, improved strength and ductility, and better stress relaxation. This new grade, therefore, has superior connectability especially when it is used with the newly designed CO/ALR connectors and special-service connectors. However, problems have been encountered even with CO/ALR devices.

In Ontario Hydro Research Division Report 78-54-K, dated February 2, 1978, M. Léger reported on a study of two CO/ALR receptacles which overheated in residential use. The undersides of the screw heads and the adjacent base plates showed evidence of dezincification, recrystallization, intermetallic-compound formation, arcing, melting, and metal transfer, all of which have been observed previously in failures of non-CO/ALR receptacles. It was postulated that one receptacle could have failed because of loose screws and a mechanical weakness caused by removal of the break-off tab, which allowed the base plate to move. The second receptacle appeared to have had tight screws and yet it showed similar damage features. Corrosion damage to the aluminum wire and the presence of high surface concentrations of chlorine *on both receptacles* were reported but not commented upon or discussed further.

Connectors designed to provide wire restraint, mechanically strong contact members, an adequate heat sink, and radiating surfaces are desirable in all electric connectors but are particularly important for aluminum. Spring follow-up to compensate for cold flow, creep, and stress relaxation also appears to be advantageous for aluminum but, if sufficient cold welding occurs on the initial contact, the maintenance of contact pressure appears to be a secondary consideration.

Table 33

FACTORS AFFECTING CONTACT RESISTANCE
OF ALUMINUM LEADING TO CONNECTION FAILURE

Author and Year of Publication	Loose Connection	Improper Surface Preparation	Break-off Tab Design	Spring-back Design	Vibration or Mechanical Disturbance	Cold Flow	Creep	Stress Relaxation	Differential Thermal Expansion
E. Lassman (1941)						X	X	X	
W.F. Bonwitt (1948)						X		X	
H. Dupre (1951)					X	X		X	X
J.P. Hayward (1952)									
Electric Light and Power (1952)						X	X		X
D.C. Hubbard (1954)		X							
R. B. Richardson (1957)		X				X	X	X	X
F. E. Sanford (1958)	X	X			X	X	X	X	
J. H. Whitley (1959)		X							
C.G. Sorflaten (1960)				X			X	X	
N. Shackman (1962)		X							
J.B.P. Williamson (1962)							X	X	X
L. Roullier (1963)				X	X		X	X	X
T. Lemke (1967)							X		X
H. Halcro-Johnston (1968)	X						X		X
R. Holm (1967)	X								
W.A. Miller (1969)						X			X
M.D. Lazar (1970)		X					X		X
H.B. Gibson (1971)		X					X		X
R.D. Naybour (1973)	X	X						X	X
R. Attermo (1973)								X	
S. Schlosser (1973)								X	
T.H. Rice (1973)						X	X		X
D.S. Reith (1974)						X	X		X
W.H. Abbott (1974)*	X		X						X
R.W. Barnard (1974)							X	X	X
R.W. Westerlund (1974)					X		X		
L. Dittman (1975)							X		
C.W. Sosinski (1975)						X	X	X	X
W.J. Meese (1976)	X								
K. Sato (1976)								X	
J.H. Whitley (1976)					X				X
M. Braunovic (1977)							X	X	X
E.R. Wallach (1977)						X			X
R.L. Hicks (1978)**	X	X	X	X	X				
R.S. Timsit (1978)**		X							X
M. Léger (1978)**									
R. Patterson (1978)**									

*Consumer Product Safety Commission: *Report on Public Hearings*, April 1974;
  Aluminum Wiring Meeting, August 1974 (transcript).
**Commission of Inquiry on Aluminum Wiring Hearings, 1977-78 (transcripts).

Fretting Corrosion	Oxidation	Corrosion	Diffusion-Segregation Intermetallics	Zinc, Cadmium Plating, and Steel Screws	Current	Current-Arcing Overload-Short Circuit	Electroplasticity	Storage	Undetined	Author and Year of Publication
										E. Lassman (1941)
		X								W.F. Bonwitt (1948)
		X								H. Dupre (1951)
		X								J. P. Hayward (1952)
	X	X								*Electric Light and Power* (1952)
						X				D.C. Hubbard (1954)
	X	X								R.B. Richardson (1957)
	X	X				X				F.E. Sanford (1958)
	X									J.H. Whitley (1959)
		X								C.G. Sorflaten (1960)
										N. Shackman (1962)
	X								X	J.B.P. Williamson (1962)
	X					X			X	L. Roullier (1963)
	X	X								T. Lemke (1967)
	X	X				X				H. Halcro-Johnston (1968)
		-	X							R. Holm (1967)
	X	X								W.A. Miller (1969)
	X									M.D. Lazar (1970)
	X	X								H.B. Gibson (1971)
	X			X						R D. Naybour (1973)
	X									R. Atterno (1973)
										S. Schlosser (1973)
	X	X								T.H. Rice (1973)
	X									D.S. Reith (1974)
X			X							W.H. Abbott (1974)*
	X	X	X							R.W. Barnard (1974)
										R.W. Westerlund (1974)
	X	X								L. Dittman (1975)
	X	X								C.W. Sosinski (1975)
				X						W. J. Meese (1976)
										K. Sato (1976)
X										J.H. Whitley (1976)
X			X				X			M. Braunovic (1977)
										F.R. Wallach (1977)
X		X		X		X		X	X	R.L. Hicks (1978)**
X			X	X					X	R.S. Timsit (1978)**
		X		X		X				M. Léger (1978)**
		X				X				R. Patterson (1978)**

The most diligent and experienced investigators in the contact field believe that there are basic mechanisms, as yet unknown, that are responsible for connection failures. The effects of thermal and mechanical stresses and of intermetallic compounds are understood incompletely. The dezinc-ification of brass and the redistribution of zinc at contact surfaces are unexplained. An explana-tion is necessary, since these latter two phenomena were observed in both service and test failures of CO/ALR and non-CO/ALR receptacles by Ontario Hydro, and in receptacles removed from Arvida after 28 years of service and examined by the Research Laboratory of Aluminum Com-pany of Canada, Ltd. The presence of a loose screw on each of the Arvida receptacles examined is puzzling and unexplained. Finally, there are the recent examples of unexplained thermal runaway observed during fundamental studies of aluminum contacts in vacuum being carried out under joint sponsorship of Canadian Electrical Association and Aluminum Company of Canada, Ltd. It will be difficult to design entirely safe and reliable electric connectors until these basic mechanisms are discovered. The laboratory and service testing required to determine these mechanisms is being carried out on a continuing basis by cable manufacturers and device manufacturers throughout the world and in Canada. Here the work is being conducted and sup-ported by the Canadian Electrical Association, Aluminum Company of Canada, Ltd., Ontario Hydro, the Canadian Standards Association, and device manufacturers.

2.6   Laboratory Testing and Technical Investigations of Wiring Systems

In recent years a considerable amount of technical work has been done in Canada and the United States to compare the performance of various types of wiring materials and devices, to study failed devices obtained from the field, and to conduct fundamental experiments essential for understanding the mechanisms by which wiring devices fail. The Commission of Inquiry on Aluminum Wiring has obtained many reports from the Canadian Standards Association, Ontario Hydro, Aluminum Company of Canada, Ltd., Alcan Canada Products Limited, Underwriters' Laboratories, Inc., the United States National Bureau of Standards, and the United States Consumer Product Safety Commission. Several witnesses testified at the Commission's hearings about their experimental results and their technical interpretations of the observed phenomena in aluminum- and copper-wiring terminations. In Section 2.6 the Commission has summarized both the organizations' reports and the witnesses' technical findings and has drawn certain conclusions.

2.6.1   The Canadian Standards Association and Underwriters' Laboratories, Inc.

The technical findings of these two organizations are discussed together because, from the evidence, it is clear that a very close working relationship exists between Canadian Standards Association (CSA) and Underwriters' Laboratories, Inc. (UL) of the United States. There is a continual exchange of technical information between the two organizations through general liaison and through reciprocal membership in technical committees. This exchange of information is important since there are general similarities in the Canadian and United States device designs, installation practices, and overall household electric-system usage. Canada and the United States constitute a common market for most of the consumer products. In general, the Canadian Standards Association has acted more slowly and more cautiously so that not all results from the United States can be applied directly in Canada.

The main purposes of certification testing by the Canadian Standards Association and Underwriters' Laboratories, Inc. are to insure that a reasonable safety level is maintained and that certain design features (for example, spacing between live parts, dimensions) are standardized.

a.   Underwriters' Laboratories, Inc. 1954 Report on Aluminum Wiring. In 1954 UL issued a comprehensive report on its research on aluminum building wires and connectors (Underwriters' Laboratories, Inc., Bulletin of Research 48, by C.W. Zimmerer and F. Neumer, September 1954). The investigation covered the electric and mechanical properties of aluminum wire as well as the effects of corrosion but *did not* cover typical terminations encountered in such wiring devices as receptacles, switches, and pigtail connectors. The results indicated that:

1. Semi-annealed or half-hard aluminum conductors showed the same ability as copper to withstand flexing without failure.
2. Galvanic corrosion does not manifest itself as a serious problem for normal installations under ordinary and commercial atmospheres. Outdoor exposure tests conducted in Pittsburgh and New Orleans for over 500 days showed little difference in degree of corrosion between connections employing copper and aluminum conductors. Corrosion that did occur was no more severe whether dissimilar metals (copper, brass, and aluminum) or similar metals were in contact.
3. Short-circuit tests at currents of 5,000 and 10,000 amperes indicated that an AWG-12 insulated aluminum conductor was damaged more quickly than an AWG-14 insulated copper conductor. Similar damage was noted, but to a lesser degree, in an AWG-10 insulated aluminum conductor; in this case, the damage was confined to the insulation, and no melting of the AWG-10 aluminum conductor occurred.

b.   Underwriters' Laboratories, Inc. 1969 Field Survey. In late 1968, UL started to receive reports of difficulties in the field use of insulated aluminum building wire. In May 1969, in order to secure information concerning these difficulties, Underwriters' Laboratories, Inc., in conjunction with the United States National Electrical Manufacturers Association, sponsored a field survey involving two questionnaires. One questionnaire was mailed to electrical contractors and inspectors and the other to manufacturers and users of electric-control equipment and related devices. UL does not consider the results of the survey statistically reliable since only 14% to 18% of the two questionnaires were returned. Nevertheless, UL considers the following conclusions to be of significance:

1.   Of all the failures of terminations reported, those with copper wire were only about 45% of those with aluminum wire.
2.   Taking into account that copper wire was used four times as much as aluminum wire in the time period under study, termination problems with aluminum wire were approximately seven times more frequent than with copper wire.
3.   Certain specific service-equipment items and circuit breakers — that were associated with reported failures in both copper and aluminum conductors — were identified.

c.   Development of CO/ALR Test Specification. As a result of the above survey, Underwriters' Laboratories, Inc. initiated a programme to develop better termination systems and better aluminum conductors for residential aluminum wiring. Because wiring systems and devices are designed to last a long time, normal operation does not offer a sufficiently quick method of testing; hence, tests using overloading, weak connections, and fast cycling must be used to get results in less time.

Heat-cycle testing is used almost universally in laboratories to evaluate wiring devices. It is believed that this mode of testing brings out the combined effects on performance of workmanship, rapid oxide formation, creep, and differential thermal expansion. Underwriters' Laboratories, Inc., after discussions with the manufacturers of wiring devices and cables and after lengthy laboratory experimentation, adopted a revised heat-cycle test procedure for the certification of wiring devices intended for use with aluminum conductors. In this procedure a current of 40 amperes is passed through a device rated for 15 amperes for $3^1/_2$ hours of each cycle, followed by 1/2 hour with the current off. The wire is disturbed after the 25th and 125th cycle, and 500 heat cycles comprise the total test. The device passes the test if, at the end of heat cycling, the following conditions have been met:

1.   The temperature of no termination point exceeds the average temperature of all points by more than 10°C.
2.   The temperature rise at no termination point is greater than 100°C.

The initial torque for terminations in these tests is 6 lb-in. This torque is much lower than necessary for a sound connection, but UL, after experimenting with several torque levels, discovered that the use of higher torques inordinately prolonged the duration of the test; in consequence, the torque of 6 lb-in used in tests did not have any relationship whatsoever to any torque expected under field conditions. A complete heat-cycling test sequence takes over 80 days.

Underwriters' Laboratories, Inc. observed that steel screws showed a higher failure rate than brass screws, that the use of an oxide-inhibitor paste improved long-term performance, and that the torque strongly influenced connection life. For example, with torque levels of 6 to 8 lb-in, overheating may occur in less than 500 cycles; by increasing the torque for the same device to 10 lb-in, the life of the connection is extended to over 4,000 cycles.

Devices that pass the above tests are labelled CO/ALR (copper/aluminum revised). By 1972 UL had adopted the CO/ALR test specification and these receptacles were produced subsequently in the United States.

In 1975 Canadian Standards Association adopted the CO/ALR test specification C22.2-42P-1975 which Underwriters' Laboratories, Inc. had developed. Prior to 1975, wire connectors for copper or aluminum conductors (except push-in devices for aluminum between 1970 and 1974) were required to be heat-cycled 42 times, using approximately 166% rated current with no more than 5°C. temperature change between the 1st and 42nd cycle. Since adopting the CO/ALR test specification, the Canadian Standards Association Testing Laboratories have conducted a large

number of heat-cycling tests on devices submitted to them for certification. Since receptacles in 20-ampere residential circuits are not in very common use in Ontario, most of the CO/ALR tests were done with AWG-12 wire at 40 amperes and not with AWG-10 wire at 53 amperes.

d.   Aluminum Conductors. A test requirement has also been developed by Underwriters' Laboratories, Inc. for aluminum conductors. In this test, an AWG-12 conductor is connected to a receptacle using steel binding-head screws. The receptacle assembly is then subjected to the heat-cycle test described above. It has been found necessary to develop new aluminum alloys to pass the test. The successful aluminum-conductor materials contain controlled amounts of magnesium and iron.

As long ago as January 1952, CSA carried out a laboratory investigation to determine the suitability of the terminals then in use in residential wiring devices for making connection to aluminum conductors in sizes AWG-8 and smaller. They concluded that a proper connection could be made with solid-aluminum conductors without exercising more care than that used normally when connecting copper conductors. The report on this investigation provided to the Commission is very brief and it is difficult to determine how this investigation was carried out. From the evidence it is now clear that the field experience with aluminum wiring has proven to be contrary to the above opinion that the installation of aluminum wiring devices requires no additional care.

Information provided by CSA indicates that early in 1966 the various technical subcommittees of the Association discussed at length the increasing use of aluminum conductors in residential wiring. Technical information for these meetings, as is the usual practice, came from a variety of sources, such as Underwriters' Laboratories, Inc., Canadian General Electric Company Limited, Alcan Canada Products Limited, Aluminum Company of Canada, Ltd., and the Canadian Standards Association Testing Laboratories, as well as verbal inputs from the members of the technical subcommittees. The CSA Testing Laboratories did not do any extensive testing at this stage. It is apparent that there was general awareness of the differences between copper and aluminum, but very little direct laboratory testing, and limited field experience with, the use of aluminum in residential wiring systems. For example, at this stage there were no data to indicate that zinc plating might not be satisfactory for devices wired with aluminum. In October 1966 the Canadian Standards Association issued *Electrical Bulletin No. 655* (Exhibit 22-B), which provided to the residential-wiring industry general guidelines about aluminum conductors.

In 1951 CSA had stipulated that aluminum conductors must have a minimum aluminum content of 99.45%. This grade of conductor material is often called the EC (electric-conductor) alloy. In 1976 a different designation, Alloy 1350, was adopted. This alloy is essentially similar to the EC alloy, and a draft bulletin giving its chemical composition is under consideration. In 1977 a new aluminum-conductor material, ACM, was recognized by a specification of the Canadian Standards Association. In July 1972 Underwriters' Laboratories, Inc. initiated a programme for recognizing similar aluminum alloys for use in residential wiring systems. The essential difference, it appears from the information provided, lies in the inclusion of 0.25% magnesium, which alters the surface mechanical properties of the aluminum wire and makes possible a better connection under a binding-head screw. Understandably, almost all of the technical information on this matter is proprietary, and CSA has no way of conducting any metallurgical investigations in its own laboratory and must rely solely on information provided by the manufacturers.

Underwriters' Laboratories, Inc. considers that the performance in CO/ALR tests of the new alloy materials is superior to that of EC-grade aluminum. CO/ALR tests conducted in Canada indicate that receptacles wired with NUAL (the new aluminum-conductor material from Alcan Canada Products Limited) have a lower temperature rise than those wired with Alloy 1350 (EC-grade aluminum).

e.   Devices of the Push-in Type. From the information provided by the Canadian Standards Association, it is apparent that as early as 1966 the technical subcommittees were uneasy about the use of spring-loaded terminations (which are commonly used in devices of the push-in type) with aluminum conductors. *Electrical Bulletin 655* prohibits this type of connection with aluminum wire. In July 1968 a Canadian manufacturer, Smith & Stone Limited, approached the Canadian Standards Association for approval of a receptacle of the push-in type for use with both copper and aluminum wire. The Canadian Standards Association conducted tests on wire

bending, heat cycling for 42 cycles, limited short circuits, and wire pull-outs; and issued a fact-finding report which concluded that there were no significant differences between AWG-12 aluminum and AWG-14 copper conductors when used with this receptacle. A scrutiny of the test results indicates that the performance of the copper wire was marginally superior under some bend tests and under limited short-circuit tests at 200 and 1,000 amperes. It should be noted that a current of 5,000 amperes is used for short-circuit testing of residential circuit breakers but no short-circuit tests are prescribed for any receptacle.

The Advisory Council for Electrical Safety of the Canadian Standards Association did not approve the use of this type of receptacle either in October 1969 or in June 1970 when a slightly modified design was submitted by the manufacturer for approval. Several members of the Advisory Council for Electrical Safety were unhappy about the use of receptacles of the push-in type with aluminum wire since there was no indication of the maximum temperatures that would be reached at the terminals when prolonged loads were fed through the receptacles and since the field experience with these receptacles — even with copper wire — was "questionable." Nevertheless, in October 1970, through *Electrical Bulletin No. 799* (Exhibit 22-B), the Canadian Standards Association approved receptacles with push-in terminals for use with aluminum wire. Examination of comparative heat-cycling data for an AWG-12 aluminum conductor and an AWG-14 conductor, when connected to a receptacle of the push-in type made by Smith & Stone Limited, indicates that at the end of 500 cycles of tests there is a higher temperature rise for aluminum wire than for copper wire. The above bulletin specifies a test current of 15 amperes turned on and off for periods of 12 minutes' duration in every cycle. These heat-cycling tests are not as onerous as those in current use for CO/ALR devices.

It seems that, although only one make of receptacle of the push-in type was authorized for use with aluminum wire, some other makes — authorized for use with copper only — in fact were used with aluminum in some cases. Some of these receptacles were made so that they incorporated both binding-head screws and push-in terminations.

Field problems with receptacles of the push-in type connected to aluminum wire were recognized early in 1974 and the approval for their use with aluminum was withdrawn. In April 1974 *Electrical Bulletin No. 943* (Exhibit 22-B) carried instructions to manufacturers to prevent the use of aluminum wire with devices of the push-in type by insuring that the openings provided for copper wire of AWG-14 were too small to take the larger aluminum wire of AWG-12. Because no records were kept, it is virtually impossible to ascertain how many receptacles of the push-in type have been installed in Ontario in residential circuits wired with aluminum conductors or where they are located, and no attempt could be made to recall the receptacles.

The above experience clearly points out that it is very difficult to equate laboratory-test results to life expectancy in the field. To be able to do so, a fundamental understanding of the physical failure mechanisms is necessary and then the device-certification tests in a laboratory must be designed to accelerate the critical-failure mechanisms. Unfortunately, the Canadian Standards Association technical subcommittees rely too heavily on the laboratory data provided by the interested manufacturer about any new device. It appears that the Standards Division of CSA does not have adequate resources to commission independent laboratory studies to appraise and evaluate new devices submitted to them for certification.

f.   Tests in Thermally Insulated Walls. At the request of the Commission, the Canadian Standards Association conducted temperature-rise tests in which 15-ampere CO/ALR receptacles were installed in a thermally insulated wall. The tests indicate that:

1.   A load of 26 amperes plugged into an insulated receptacle produces the same rise in temperature as a current of 40 amperes if the receptacle is installed in free air, as is the case in a CO/ALR test. If a feed-through load is used, instead of a load plugged into the receptacle under test, a marginally higher current of 27 amperes is needed to give the same temperature rise. This indicates that heat generated at the plug-to-socket terminals contributes to the temperature rise of the binding-head screw terminals inside the receptacle. Based on a steady current of 15 amperes in a receptacle installed in a home, the CO/ALR test current of 40 amperes in open air (equivalent to 26 or 27 amperes in the wall of a house) produces a heat dissipation at the binding-head screw terminals of approximately

three times that which would be encountered with 15 amperes [heat dissipation is proportional to the square of the current and $(26/15)^2$ equals 3]. In this respect the CO/ALR test is quite severe.

2. The ambient temperature inside a shallow receptacle housing in an insulated wall may be approximately 30°C. higher than the room temperature when a load of 15 amperes is plugged into the receptacle. Under these conditions the temperature at the hottest point, the break-off tab, may reach 76°C. (assuming a room ambient temperature of 27°C.). If the current is 18 amperes, the temperature of the break-off tab may rise to above 100°C. It should be noted that overcurrent-protection devices in a 15-ampere circuit often do not operate until a current level of 18 amperes is reached.

Additional tests have been done using an AWG-10 aluminum conductor (Alloy 1350), and the results are similar.

g. Miscellaneous Tests. Additional test data on wiring devices provided by the Canadian Standards Association indicate that:

1. At low torques steel-screw receptacles perform marginally better when connected to copper AWG-14 wire than those wired with aluminum AWG-12.
2. At a low torque of 1 lb-in — which, on visual inspection, may still appear as a tight connection — CO/ALR-grade receptacles will fail in the first few heat cycles if subjected to the CO/ALR tests.
3. Short-circuit tests of up to 1,000 amperes in magnitude do not impair the test performance of pigtail connectors or receptacles.
4. Subjection of the receptacles to a water spray does not impair their performance under heat-cycle tests.
5. Several non-CO/ALR receptacles from both the so-called hospital and the standard grades can pass CO/ALR tests with AWG-12 aluminum wire at 40 amperes. The receptacles with unplated brass terminals are the most successful.

h. Crimp Connections. The Canadian Standards Association also investigated the adequacy of some crimp-type pressure connections for application to the residential wiring system. The Association examined five different types of tools for making these connections, some of which are intended for making connections in automotive electric-wiring systems but are generally available to the public. Tests were carried out with attachments to CO/ALR-grade receptacles with currents of 15, 35, 50, and 53 amperes. Many of the tested connections overheated with both copper and aluminum conductors. The study recognized that the technology of crimped or compression termination is not new and while, in certain forms, this method might prove an adequate solution for terminating aluminum conductors, its implementation for residential branch circuits would be premature at present. Furthermore, the study recommended that all facets of the technology should be examined before any systems of crimped terminations are adopted for the residential branch-circuit wiring.

i. The Canadian Standards Association Task Force on Aluminum Terminations. The Canadian Standards Association established a Task Force on Aluminum Terminations in May 1974. The Task Force formed a Working Group in June 1975 to investigate the technical aspects of aluminum-wiring terminations in residential branch circuits. The members of the Task Force and the Working Group were drawn from the Canadian Standards Association and the various sectors of the electrical industry. The Consumer Association of Canada is represented on the Task Force. By the end of 1977, the Task Force had met five times. The Working Group met fourteen times between July 1975 and May 1976, and then submitted a final report to the Task Force. The Working Group collected technical information from Ontario Hydro and Canadian manufacturers of wire, wiring devices, and associated equipment. Information was also obtained from discussions with experts in relevant areas from the United States, such as W.H. Abbott, of Battelle Columbus Laboratories, Columbus, Ohio; W.A. Farquhar, of Underwriters' Laboratories, Inc., Melville, New York; and N.T. Bond, of Alcoa Conductor Products Company, Massena, New York.

The conclusions and recommendations of the CSA Working Group are noted below:

1. The incidence of overheating failures in connections involving either copper or aluminum wire and binding head screw connections (as found on panelboards, receptacles, etc.), pigtail connections and push-in type connections can be reduced.
2. This reduction will require changes in and more stringent enforcement of standards covering the aluminum wire material and the wiring devices to which the wire is connected. In addition the installation codes must be improved and more strictly enforced.
3. The specific details of changes required are complex, involve specialized knowledge not readily available to the working group and all of them could not be determined in the time available. It is possible to indicate the general nature of changes and recommend these be considered by specialized groups.
4. Residential branch circuits are subjected to frequent on-off and high inrush loads, which can stress certain types of connections more severely than continuous loads. Standards will have to recognize these types of loads.
5. The connection stability of solid aluminum wire can be improved. Such an improvement should be made. To ensure this, a suitable test should be developed and added to the standard.
6. The CO/ALR requirement for binding head screws represents a major improvement in achieving reliable connections to aluminum conductors.
7. The performances of CO/ALR devices and aluminum conductor wires depend on manufacturing procedures which can change from time to time. The Canadian Standards Association (CSA) should investigate Underwriters' Laboratories Incorporated (UL) methods of monitoring the manufacturing procedures and adapt existing inspection procedures to ensure an equivalent or better level of quality assurance.
8. Life of binding head screw, panelboard and most other residential branch circuit wire connections depends on the installation torque. These torques are presently not controlled and low torques have been a cause of failures. The committee for the Canadian Electrical Code Part I and other installation codes should introduce specific requirements for installation torques.
9. The fundamental factors affecting connector life were found to be complex and not completely understood. Research activity directed to completing this understanding and putting test standards on a more fundamentally sound basis should be encouraged.
10. Screw type terminals forming connections to aluminum wire in residential branch circuit wiring components other than CO/ALR (such as panelboards and line voltage thermostats) are fabricated using zinc plated steel and brass current carrying parts. The standard covering these connectors should be revised to include more extensive heat cycle tests. A temporary design standard should be introduced until more demanding performance standards are developed.
11. The standard covering pigtail connectors should be upgraded to more accurately recognize field service conditions.
12. Some push-in connections to copper wire are less reliable than binding head screw connections. A more demanding test standard should be required for push-in connectors to ensure a life equal to that achieved with binding head screw connections.
13. The identification on individual products is not changed to reflect standard and product changes. This leads to confusion as to the effect of these changes. Consideration should be given to developing a uniform date code system for marking individual component parts of the branch circuit wiring system.

The Canadian Standards Association has already acted on some of the above recommendations and an overall device-improvement programme is under discussion. To this end, the Committee on the Canadian Electrical Safety Code have reconstituted the Task Force on Aluminum Terminations as a Standing Committee on Branch Circuit Wiring Systems.

2.6.2 Aluminum Company of Canada, Ltd., and Alcan Canada Products Limited

This section describes four investigations made by these companies.

a. Heat-Cycle Testing of Receptacles and Wire Connectors. The Research Centre of the Aluminum Company of Canada, Ltd., in Kingston, has been investigating commonly available residential-grade receptacles and wire connectors since 1973. The two main purposes of these investigations have been:

1. To determine the relative performance of various makes and types of receptacles and wire connectors used in residential branch circuits when wired with aluminum (Alloy 1350), copper, and new aluminum alloys (ACM and Alcan NUAL).

2. To determine the influence of receptacle and connector materials, including platings, on the performance of electric connections in a residential branch-circuit system.

In these investigations heat-cycling tests were performed at 25, 35, and 40 amperes for binding-head screws and pigtail connectors.

During 1973 and 1974, seven makes of Canadian pre-CO/ALR receptacles with brass screws (plated and unplated), one United States make of pre-CO/ALR receptacle with steel screws, and one United States make of CO/ALR receptacle were subjected to 1,000 heat cycles of $3^1/_2$ hours on and 1/2 hour off at 25 amperes. Ten specimens of each make were tested. AWG-12 EC-grade aluminum conductor was used and all screw terminals were tightened to 6 lb-in torque. The Commission has drawn the following conclusions from this series of tests:

1. There was a wide variation in the electric performance of binding-head screw terminations with aluminum wire. Presumably the certification procedure at that time was inadequate for differentiating between the various grades.
2. Zinc plating was the common factor in most cases of failure (greater than 100°C. rise in temperature).
3. The particular make of United States pre-CO/ALR receptacles tested had steel screws and zinc plating but did not fail at the stated current level, nor did the terminal temperature rise above 5°C. after the 25th heat cycle. The report did not provide sufficient information to determine the reasons for this performance.

During 1974 and 1975, additional tests were performed with Canadian pre-CO/ALR and United States CO/ALR receptacles that were wired with AWG-14 copper or AWG-12 aluminum (EC-grade and NUAL) conductors. These tests were performed in accordance with CO/ALR-test specification C22.2-42P-1975. Five specimens of each make were tested. The Commission has drawn the following conclusions from the results of these tests:

1. Pre-CO/ALR zinc-plated terminals failed very often with EC-grade aluminum, NUAL aluminum alloy, and copper conductors. Out of 15 samples tested with each type of conductor, 13 failed with EC-grade aluminum, 10 failed with NUAL, and six failed with copper conductors.
2. Pre-CO/ALR non-zinc-plated terminals also failed with EC-grade aluminum-alloy conductors but no failures were recorded with either NUAL aluminum conductors or with copper conductors.
3. No failures were recorded with CO/ALR receptacles that were connected to any aluminum conductor but one freak failure was recorded (at the 255th cycle) with a United States make of CO/ALR receptacle wired with a copper conductor.

In 1977 additional tests indicated that unplated brass screws performed better than zinc-plated steel screws with both EC-grade and NUAL conductors. The NUAL conductor showed significantly fewer failures (three out of 15) compared with the EC-grade conductor (11 out of 15) when connected to zinc-plated steel-screw terminals.

Since 1975, the Research Centre of the Aluminum Company of Canada, Ltd., has investigated the performance of various types of pigtail connectors and has assisted with the development of a new design of connector, designated by the Canadian Standards Association as a special-service connector. The salient conclusions from this long series of tests are summarized below:

1. Set-screw-type pigtail connectors with unplated brass screws performed better than those with cadmium-plated steel screws, when tested at 25 amperes for 500 heat cycles, at tightening torques of between 3 lb-in and 4.5 lb-in.
2. For connecting two solid conductors (copper and aluminum), the substitution of a copper-alloy helix for a ferrous helix in twist-on connectors markedly improved the connector performance when heat-cycled at 35 amperes and at a torque of 4 lb-in or more.
3. When used for connecting extra-flexible copper AWG-14 to solid-aluminum AWG-12 wire, the new design for the twist-on connector — now designated as a special-service connector — gave satisfactory performance when heat-cycled at 35 amperes and tightened to torques of more than 3 lb-in.

b. *Metallurgical Studies of Aluminum-Wiring Terminations.* In 1976 the Aluminum Company of Canada, Ltd. was awarded a contract by the Canadian Electrical Association (CEA No. 76-19)

to study electric connections involving aluminum wire. The work on this contract is being conducted at the company's Kingston Research Centre. In addition to the work on this contract, researchers have conducted fundamental investigations of physical phenomena in electric contacts involving aluminum and copper conductors.

In one study (Exhibit 187), the Centre evaluated the role of certain physical processes (for example, growth of intermetallics, current flow through oxide films, stress relaxation, oxidation at the interface, fretting corrosion) in contact performances for both copper and aluminum conductors. In this study, except for fretting corrosion, ideally static contacts were assumed. This is a crucial assumption. The Commission has made the following summary of the Centre's report:

1. Mechanical properties and fracture strength of surface oxide films played an important role in determining the initial contact resistance of a junction. Information on mechanical properties of very thin, natural metal-oxide films was scant. Obviously, mechanically strong surface-oxide films led to a higher initial contact resistance than did weak or brittle films. Some information existed on Al_2O_3, but the lack of corresponding data on copper and brass made it impossible to compare quantitatively the likely differences between aluminum and copper contact systems.

2. The presence or growth of an oxide at a contact interface was suggested as a possible degradation mechanism. If the contact temperatures were below approximately 100°C., this process was unlikely to be of significance in junctions involving most metals, including copper, aluminum, or brass. This was because surface oxide films generally did not grow indefinitely but instead reached limited thickness values of a few angstroms at these temperatures. In other words, contact temperature is a crucial parameter.

3. Copper oxides occur in many phases, including cupric (CuO) and cuprous (Cu_2O). Cupric oxide is relatively a good electric conductor, with a specific resistance of 10^2 to 10^3 ohm-cm. Cuprous oxide (and some other phases) are p-type semiconductors and their resistivity rapidly decreases with increase in temperature. At a temperature of 100°C. the specific resistance of cuprous oxide is approximately 4.5×10^5 ohm-cm. By contrast the electric resistivity of aluminum oxide, Al_2O_3, is approximately 10^{14} to 10^{16} ohm-cm. Taking these typical values and assuming a film area of 1 cm² and thickness of 20 Å, the copper-oxide film presents a resistance of 9×10^{-2} ohm and aluminum-oxide film a resistance of 11 ohms. Typical metal-bridge resistances for copper-brass and aluminum-brass contacts lie between 2.6×10^{-3} and 2.9×10^{-3} ohms. Film resistances of copper and aluminum oxides may have substantial differences, but their role in ideally static contacts may not be significant.

4. Intermetallic compounds in copper-brass and aluminum-brass contact couples would be formed if the temperature was sufficiently high and if enough time elapsed. Most intermetallic compounds are usually characterized by a relatively high resistivity and their growth at an electric-contact interface would result in an increase in the resistance of the junction. Unfortunately, diffusion constants for aluminum-to-brass and copper-to-brass were not fully established. For an aluminum-to-copper contact system at a temperature of 100°C., a 5-micron layer of intermetallics would take 150 years to grow! The researchers concluded that if the rate of intermetallic growth for aluminum-to-brass was not too different from that for aluminum-to-copper, the presence of an intermetallic layer would have a negligible effect on contact resistance over a long period of time, provided the contact temperature was below 100°C.

5. Fretting corrosion occurred when interfacial motion of sufficiently large magnitude was allowed to occur in a contact. This motion presumably induced the break-off and sliding of formerly contacting asperities across the interface. The importance of fretting was difficult to assess. If fretting were operative, its effect should have been more pronounced during transient heating and cooling, especially in bi-metallic contacts (aluminum-to-brass), because interfacial motion induced by differential thermal expansion of the two metals might be serious. However, the researchers concluded that the fretting phenomenon should operate to roughly the same extent in both aluminum-to-brass and copper-to-brass contact systems, particularly since shearing stresses for breaking metallic bridges were of the same order of magnitude for equal ratios of a-spot area to total contact area.

6. In most mechanically held electric contacts, the onset of metal creep led to a drop in contact pressure. However, even for a large decrease in contact pressure, the contact resistance did not generally rise after a good contact had been made; if the reduction in contact pressure also led to micromotion of contact a-spots, it might well initiate electric failure through increased fretting corrosion. Published data were not available to make possible quantitative assessment of this effect for aluminum-to-brass or copper-to-brass contact systems.

c. *Investigations Sponsored by the Canadian Electrical Association.* The fundamental electric-connection studies at the Kingston Research Centre, sponsored by the Canadian Electrical Association (see 2.6.2 *b.*), are yielding significant results. For these studies the researchers have constructed a high-vacuum test chamber so that the environment of an ideally made electric contact can be controlled accurately. This work proposes:

1. To determine the composition of interfacial layers formed as a result of cross-boundary diffusion in various bi-metallic electrical couples (EC aluminum-*a* brass and plated-*a* brass) both in vacuum and in oxygen gas.
2. To investigate the effect of these interfacial diffusion layers on the electrical contact resistance characteristics of the bi-metallic couples also in a vacuum and in an oxygen gas environment.

Two progress reports have been issued to date on this work, the first in October 1977, and the second in April 1978. Only tentative observations may be made from the results so far. Some of these are:

(i) Diffusion. Diffusion of indium, tin, and zinc platings in a plated-brass system was studied over a temperature range of 80°C. to 150°C. The rates of formation of intermetallic compounds resulting from diffusion were measured by exposing plated-brass samples to different temperatures for various lengths of time. The growth of the diffusion bands was found to follow the following equation:

$$h^2 = \left\{ k_o \exp\left(-Q/RT\right)\right\} t \qquad (30)$$

where

$$
\begin{aligned}
h &= \text{thickness of the diffusion layer} \\
k_o, Q &= \text{constant} \\
R &= \text{Boltzmann's constant} \\
T &= \text{temperature} \\
t &= \text{elapsed time}
\end{aligned}
$$

The values of k_o and Q for zinc, indium, and tin platings are given in Table 34.

Table 34

DIFFUSION CONSTANTS FOR
METALS IN BRASS

Metal	k_O $(cm^2 sec^{-1})$	Q $(kcal\ mol^{-1})$
Zinc	69.1	22.9
Indium	1.25×10^{-7}	9.72
Tin	5.18×10^{-9}	7.88

Commission's note: This table, identical to Table
27, is reproduced here for ease of reference.

Clearly, zinc diffuses into brass very much more rapidly than either tin or indium. Diffusion studies in an aluminum-to-brass contact system gave the relationship:

$$h^2 = 3.46 \times 10^{-4} \exp\left(-2.21 \times 10^3/RT\right)t \qquad (31)$$

These studies have not been completed yet.

Elemental analysis of the interface indicated that copper diffused from the brass into aluminum, but that little aluminum diffused into brass.

(ii) Contact Resistance. Contact-resistance work was performed for aluminum-to-aluminum contacts as well as for aluminum-to-brass contacts. In vacuum for aluminum-to-aluminum, the contact grew through a sintering process, and the growth rate was not influenced by the presence of surface oxide films at high temperatures. At temperatures ranging from 100°C. to 350°C. the growth appeared to be due to volume diffusion; at lower temperatures plastic flow may control the sintering process.

The studies on junction growth versus residual load indicated that the removal of the load resulted in an anelastic recovery, i.e., there was a hysteresis effect. The validity of these conclusions in an oxygen atmosphere remains to be tested.

For aluminum-to-aluminum contacts, thermal runaway was observed on several occasions under the action of a constant current (13.6 amperes, with an initial junction voltage drop of 68 millivolts). In the absence of oxygen, since the experiments were done in high vacuum, several possibilities exist for this runaway. Solid impurities (such as iron, $FeAl_3$, and iron-silicon-aluminum compounds present in EC-grade aluminum) may diffuse to the contact area. Voids may diffuse into the contact area through Kirkendall migration. Dissolved oxygen may migrate to the contact area. The researchers favoured the last mechanism because microprobe analysis revealed some accumulation of both carbon and oxygen in the contact area.

Introduction of oxygen inhibits the growth of the contact area as observed in vacuum. No thermal runaway has been observed so far in the presence of an oxygen atmosphere.

Aluminum-to-brass contact studies were done mainly in vacuum. Junction growth in the presence of stable surface-oxide films was observed but did not appear to be smooth. The researchers attributed this, in part, to residual vibration of the apparatus. If this was the case, then the contact resistance of EC-grade aluminum-to-brass junctions in vacuum was considerably more susceptible to vibration, i.e., less stable than the corresponding aluminum-to-aluminum junctions. Attempts to measure junction growth as a function of temperature were not successful because the contacts went into a thermal-runaway mode for reasons that were not clear. A microprobe analysis revealed accumulation of carbon and zinc in the contact area on the aluminum surface, and carbon-and-oxygen accumulation on the brass surface. The mechanism responsible for triggering the thermal instability is being studied.

Another aspect of the Canadian Electrical Association-sponsored research at the Kingston Research Centre dealt with actual receptacle contact studies in air. Preliminary results of a study of measurements of torque-to-load resistance indicated that the presence of a lubricant at the contact surface resulted in a higher load for the same torque. However, the resistance values were not significantly affected. Experiments were conducted with EC-grade aluminum, aluminum-alloy CA10920, and copper conductors. The plating materials used for the binding-head screw were zinc, indium, or tin. The results indicated that, while certain platings or lubricants could provide significant reductions or increases in contact load for a given torque, these were not necessarily accompanied by significant increases or reductions in contact resistance. Rather, the magnitude of the initial contact resistance appeared to be dependent on other factors associated with the particular plating or lubricant. In this respect the following is the order of preference for the platings investigated: tin, bare brass, indium, and zinc.

d.   *Metallographic Examination of Aluminum-Wired Receptacles from Arvida, Quebec.* In 1948 a number of houses in Arvida, Quebec, were wired with aluminum conductors. Researchers were able to obtain from Arvida several samples of receptacles wired with aluminum as well as with copper. Report KR/78-066-5 (Exhibit 189) describes the results of an examination. Terminals from these receptacles were examined in a microprobe and in a scanning-electron microscope. The receptacles were of pre-CO/ALR type and of designs now superseded in Ontario. The neutral terminal was identified by a thin plating of nickel on the binding-head screw. All the screws appeared to be in good condition. However, those on the neutral side showed a loss of lustre, perhaps due to ageing, and some were found slightly loose. An examination of the interface in the microprobe indicated that there was a depletion of zinc on the brass side for both copper-to-

brass and aluminum-to-brass terminations. There was no evidence of zinc diffusion into either aluminum or copper. The researchers surmised that this zinc condensed on the cool sections of the brass surface away from the contact zone when the junctions were in operation.

2.6.3 W.P. Dobson Research Laboratory, Ontario Hydro

This laboratory, located in Toronto, is the principal research facility of Ontario Hydro. It has been interested for a long time in the use of aluminum conductors for the transmission and distribution of electric power, and has acquired considerable experience and expertise in terminations involving both copper and aluminum. For example, an early report (Ontario Hydro Research Report 60-369) set out theory and practice of evaluating the electric performance of power connectors. Ontario Hydro has provided the Commission with many research reports. The Commission has summarized the findings that have particular relevance to this Inquiry.

a. Panelboards. In Ontario residential units, there are in general use two types of panelboards that offer overcurrent protection: those with fuses, and those with branch-circuit breakers. In 1974 the Electrical Inspection Department of Ontario Hydro requested the W.P. Dobson Research Laboratory to investigate the performance of residential panelboards. The request was made because many panelboards with fuses had failed in the field in ways that posed a fire hazard and in any case were costly to repair. Several reports on this investigation (Ontario Hydro Research Reports 75-136-K, 75-154-K, 75-177-K, 76-301-K, and 76-407-K) were made available to the Commission. From these reports it is clear that failures of panelboards in Ontario homes were numerous: 157 failures were reported to Ontario Hydro during 1973, 1974, and the first quarter of 1975. In several instances repeated failures occurred in the same home. The data resulting from these investigations indicated that the probable causes of these failures were independent of the type of conductor used in the branch-circuit wiring and had no bearing on the relative reliability of aluminum or copper. Improvements in the laboratory testing for certification were proposed by Ontario Hydro and the findings were communicated to the Canadian Standards Association. However, the householders who may be affected were not informed of the results of the investigations.

b. Receptacles. In 1974 the Research Laboratory initiated its programme of research into the connections of residential aluminum-wired receptacles. A report summarizing the then-available knowledge on residential receptacle failure was issued early in 1975 (Ontario Hydro Research Report 75-47-K), and a laboratory investigation was launched into the various aspects of aluminum and copper branch-circuit wiring. A number of reports dealing with this receptacle-connection research have been made available to the Commission (Ontario Hydro Research Reports 75-226-K, 75-458-K, 76-14-H, E76-17-K, 76-189-K, 76-196-K, 76-325-K, 77-551-H, and 78-37-H). The salient findings of these investigations are:
1. In an effort to establish a suitable laboratory heat-cycle test procedure, experiments were conducted to measure temperature rises in receptacles for various currents (Ontario Hydro Research Report E76-17-K). The temperature rise was highest at the receptacle break-off tab. The tab operated at about 35°C. above the wire-conductor temperature. For receptacles mounted in a horizontal position in a metallic housing but with the cover removed, a current of 27.5 amperes produced a temperature rise of approximately 75°C. at the tab if the laboratory ambient temperature was approximately 25°C. Almost all of Ontario Hydro's heat-cycle testing was done at this current. This study also established that the temperature rise at the break-off tab was approximately proportional to the square of the current. The temperature rise at the receptacle terminals, under these conditions, was approximately 45°C. to 50°C. The installation torque on the binding-head screws for the purpose of these tests was 6 lb-in.
2. A cycle of 3½ hours on and 1/2 hour off, similar to that used in the present CO/ALR test, was selected for heat-cycle testing. It was estimated that a current of 27.5 amperes in an open metal housing was equivalent, from temperature-rise considerations, to 40 amperes for receptacles mounted without any housing. The laboratory selected failure criterion of

100°C. rise in temperature at the break-off tab from the commencement of the test (i.e., an overall temperature of 200°C. at the tab). The total number of cycles for these tests was 500, and both AWG-12 EC-grade aluminum and AWG-14 copper conductors were used to connect the receptacles. Several makes of CO/ALR and pre-CO/ALR receptacles were tested.

The most significant finding of the above heat-cycle tests was the relationship between the screw-terminal plating material and the survival rate. Receptacle terminals with silver-, tin-, or indium-plated screws did not experience any failures with either aluminum or copper wire. In contrast the terminals with zinc-plated screws showed a 63% failure rate with the aluminum conductor and a 20% failure rate with the copper conductor. Those with bare-brass screws showed a 5% failure rate with aluminum conductors and no failures with copper conductors. Those with nickel-plated screws showed a 40% failure rate with aluminum conductors and no failures with copper conductors.

3. A long-term heat-cycle test (up to 2,500 cycles), done with pre-CO/ALR receptacles connected to aluminum wire, indicated that 75% of eventual failures showed signs of overheating before 500 heat cycles were completed. Since some failures occurred with unplated brass screws, factors other than plating material were considered to be responsible. These other factors were not identified in the report (Ontario Hydro Research Report 76-189-K).

In receptacles that did not overheat during heat cycling there was a small temperature difference (5°C.) between the break-off tabs on the live and neutral sides. For most receptacles tested there was a direct correlation between the cycle number at which overheating occurred and the operating temperature of the screw terminal.

Ontario Hydro also examined failed samples obtained from the field. All these receptacles were wired with aluminum. Failures occurred most frequently at zinc-plated screw terminals, but several unplated brass terminals were also involved. In a large number of instances (62 out of 138) the overheated terminal appeared secure on visual inspection but in a little over half the cases the wire under the screw head was visibly loose (Ontario Hydro Research Report 76-196-K). In a majority of cases the dwellings in which failures occurred were under four years of age.

Approximately one quarter of the failures in the field involved receptacles that were wired as split receptacles. In these receptacles failures of unplated brass terminals were higher than for normally wired receptacles. The removal of the break-off tab, it was found, decreased the mechanical rigidity of the connection. This factor, coupled with the fact that split receptacles were often used with high-current appliances, may have accelerated failure. The split-receptacle application is not recognized in the current Canadian Standards Association certification specification for residential-grade receptacles. The results of the above field-failure study suggest that it should be.

4. Six samples of failed CO/ALR receptacles had been received by Ontario Hydro before about mid-1978. In some samples poor workmanship, not the receptacle, appeared to be the cause of failure. Ontario Hydro conducted comparative laboratory tests with simulated poor workmanship to observe differences in performance of CO/ALR receptacles that were wired with EC-grade AWG-12 aluminum and with AWG-14 copper. Six of the seven aluminum-wired receptacles, with an initial contact resistance of 1.58 milliohm, failed on the first heat cycle. Six out of seven of the receptacles similarly wired with copper also failed, but lasted till the 24th cycle. The tests showed that CO/ALR receptacles wired with either copper or aluminum wire eventually would fail if the workmanship was inadequate. However, time to failure for copper-wired receptacles is longer than for aluminum-wired receptacles (Ontario Hydro Research Report 78-71-H).

c. *Pigtail Connectors.* The most common type of failure that Ontario Hydro encountered in the field involved the binding-head screw connection in receptacles. In several instances, in addition, twist-on pigtail connectors had overheated. The application of this type of connection that Ontario Hydro investigated extensively was the connection of an AWG-12 solid-aluminum EC-grade conductor to an AWG-14 extra-flexible copper (41-strand) conductor. This combination of wires is found very commonly on electric baseboard-heater connections, electric-heating thermostat connections, and sometimes in automatic dishwashers.

Ontario Hydro, in their laboratory heat-cycle investigations, used an arrangement basically similar to that used for the receptacles. Two connectors were assembled in a metallic housing without the cover and a current of 27.5 amperes was used for a heat cycle of 3½ hours on and 1 2 hour off, for 500 cycles (Ontario Hydro Research Reports 76-191-K and 77-236-K). Installation torques of 4 lb-in and 6 lb-in were used for the twist-on and set-screw types of pigtail connectors, respectively. It was recognized that these torque levels represented good workmanship in the field. Moreover, to improve the connection the stranded-copper conductor was stripped 1/8th inch more than the solid conductor, and this extra length was then hooked over the end of the solid conductor. The principal variable in these tests was the combination of wires:

1. One AWG-12 solid-aluminum to one AWG-14 41-strand copper
2. One AWG-12 solid-aluminum to one AWG-14 solid copper
3. One AWG-14 solid copper to one AWG-14 41-strand copper

Approximately 200 samples were tested. The results of this investigation are summarized below and certain conclusions drawn by the Commission are also noted.

The major conclusion drawn is that pigtail connections involving solid-aluminum (AWG-12, EC-grade) and extra-flexible bare-copper (41-strand, AWG-14) conductors are less reliable than any of the other wire combinations tested. Relatively, connectors involving the AWG-12 solid-aluminum and AWG-14 solid-copper were more reliable. The appearance of connectors failing in the laboratory tests was very similar to that of the failed connectors from the field. In June 1976, the Electrical Inspection Department of Ontario Hydro banned the use of a solid-aluminum conductor with electric baseboard heaters having extra-flexible copper leads. Moreover, a repair procedure involving an extra piece of solid-copper conductor between the solid-aluminum and the stranded-copper conductors was recommended.

A statistical study compared the life expectancy of a pigtail connector joining the solid-aluminum conductor to the extra-flexible copper conductor to that of a pre-CO/ALR residential-grade receptacle having zinc-plated terminal screws (Ontario Hydro Research Report 76-236-K). The following observations may be made on the basis of this study:

1. Solid aluminum-to-stranded copper connections had a median life of 1,000 cycles.
2. Pre-CO/ALR receptacles with zinc-plated screws had a median life of 700 cycles.
   The observed difference in lives between 1. and 2. was not enough to be statistically significant at a 90% confidence limit. In other words, pigtail connections involving solid-aluminum (AWG-12, EC-grade) and extra-flexible copper (AWG-14, 41-strand) conductors were almost as unreliable as pre-CO/ALR receptacles with zinc-plated screws when connected to AWG-12 EC-grade aluminum conductors.

Ontario Hydro has been participating in a programme for upgrading pigtail connectors suitable for joining the solid-aluminum conductor to the extra-flexible copper conductor (Ontario Hydro Research Report 78-235-K). The Canadian Standards Association in May 1977 issued *Electrical Bulletin No. 1122* (Exhibit 22-C) that gave details of a new test specification for a pigtail connector intended for joining a solid-aluminum conductor (AWG-12) to an extra-flexible copper conductor (AWG-14, 19 to 41 strands). Connectors passing these tests are to be designated *special-service connectors*. Ontario Hydro evaluated one particular manufacturer's prototype of this connector which has passed the tests specified in the CSA bulletin.

In an additional series of tests some common designs of pigtail connectors with an oxide-inhibiting paste were also tested. The test procedure was essentially the same as that used in earlier investigations (Ontario Hydro Research Report 77-236-K) but for some tests the applied torque was reduced from 4 lb-in to 2 lb-in, to reflect field conditions, and a conductor-disturbance test was incorporated. From the results of this investigation the following observations may be made:

1. Special-service connectors and regular connectors in several wire combinations gave the following median test life in cycles:

	Special-Service	Regular (Cu-Al)
AWG-14 41-strand copper-to-AWG-14 solid-copper	>15,000	10,000
AWG-14 41-strand copper-to-AWG-12 solid-aluminum (EC-grade)	1,600	130

Clearly the copper-to-copper connections were far superior to the copper-to-aluminum connections. The special-service connectors with a tin-plated copper-alloy helical spring gave a more reliable performance for the copper-to-aluminum connections, but the performance of this combination was still not as good as the copper-to-copper connection with a regular Cu-Al connector containing a tin-plated steel helical spring.

2. When a piece of AWG-14 copper wire was used to connect AWG-12 solid-aluminum EC-grade to extra-flexible (41-strand) copper in a standard junction box with four regular (Cu-Al) connectors, a median life of 1,000 cycles was acheived. The torque for these tests was 4 lb-in.

3. The effect of an oxide-inhibiting compound on connector performance, when joining solid-aluminum wires, depended upon connector design and installation torque. For example, at an installation torque of 6 lb-in, a barrel, or set-screw, type of pigtail connector gave the following median lives:
   Dry, 1,600 cycles; with oxide-inhibiting paste, 1,200 cycles; with lubricant, 2,400 cycles.
   On the other hand, one design of a twist-on connector gave quite different results:
   Dry, 500 cycles; with oxide-inhibiting paste, 2,700 cycles; with lubricant, 300 cycles.
   The above results are not conclusive and additional research is necessary to establish the conditions under which oxide-inhibiting pastes may or may not be beneficial.

4. In a test involving two types of barrel, or set-screw, connectors — one with a cadmium-plated steel screw and the other with an unplated brass screw — it was discovered that the median life expectancy decreased from 1,600 cycles for the steel screw to 200 cycles for the unplated brass screw. This is a surprising result and the reasons for this behaviour are not clear.

5. Connector-disturbance tests reduced the median life expectancy of special-service connectors significantly: from over 8,000 cycles to 1,000 cycles for a combination of NUAL-grade AWG-12 and AWG-14 41-strand copper conductor.

d. Metallurgical Studies of Failed Aluminum-Wire Connections. The Metallurgy Section of the W.P. Dobson Research Laboratory has investigated metallurgical phenomena in failed aluminum-wire connections. Ontario Hydro Division Research Reports 76-14-H, 77-551-H, 78-37-H, and 78-54-K refer to examinations of failed receptacle and pigtail connectors obtained from the field. In addition, comments on these metallurgical studies are contained in Exhibit 195 and in the replies received to the Commission's technical questionnaire (Exhibit 209).

Examination of six failed pre-CO/ALR receptacles obtained from the Ottawa area (Ontario Hydro Research Report 76-14-H) revealed that overheating of aluminum-wired receptacles in service produced temperatures in excess of those required for recrystallization and consequent softening of cold-worked aluminum and brass components (i.e., the temperatures were in excess of 300°C.).

The surfaces of brass components on two overheated receptacles had suffered dezincification in the areas of maximum temperature. There was no evidence that screw plating material (four samples with zinc coating and two with a silver wash) had diffused into the aluminum wire. In some cases the plating was very thin. Minor fretting damage was observed on one sample.

Early in 1978 two CO/ALR receptacles, which failed prematurely by overheating, were examined by the laboratory's Metallurgy Section (Ontario Hydro Research Report 78-54-K). The receptacles had indium-tin platings. In one receptacle the terminals were clearly loose, while impressions on the brass base plate of the other were clearly visible. The Ontario Hydro researchers were able to establish that at least one of the receptacles had its terminals initially tightened to between 3 lb-in to 5 lb-in. There was ample evidence of arcing on both receptacles between the screw head and the wire, between the underside of the wire and the base plate, and at the threads between the screw and the base plate. In one receptacle, which had been wired as a split receptacle, there was arcing between the live screw heads, and the terminal assembly was loose in the plastic moulding. There was evidence of dezincification of the screw head and the base plate, and a high concentration of zinc was observed. In the case of the receptacle with an initial torque of approximately 5 lb-in, the researchers were unable to identify the cause of failure. They concluded that motion of the base plate accelerated the failure of the split receptacle with a relatively loose wire.

Ontario Hydro also conducted metallurgical investigations of devices obtained from two houses in which fires, suspected to be due to electric wiring, had occurred (Ontario Hydro Research Reports 77-551-H and 78-37-H). In one instance the fire occurred in the vicinity of an aluminum-wired duplex receptacle situated in an outside wall. The receptacle, which was damaged severely, had a steel screw. The initial torque on the screw was estimated to be around 3 lb-in. The temperature of the screw, at one time, had been close to 600°C. The high temperature was caused by the malfunction of the device and not by the burning of the receptacle in a fire of external origin (Report 77-551-H). In the other fire, aluminum wiring was used to connect permanent baseboard heaters. Pigtail connectors from the baseboard and other wiring devices were subjected to an extensive metallurgical examination. The researchers concluded that:

1. All of the damage noted in the components of the baseboard heater could have resulted from an intense fire external to the baseboard heater.
2. No other metallurgically examined component from the fire scene exhibited damage that could be attributed to electric failure of the component in question.

Other metallurgical evidence provided by Ontario Hydro clarified the role of diffusion and intermetallics on aluminum-wiring examinations. Their calculations showed that if the contact was operating at 90°C., the resistance of an intermetallic layer might become comparable to the contact-constriction resistance in about 30 years. The temperature required to have the same effect in 10 years would be closer to 100°C. and in five years would be slightly above 100°C. The critical role of the device temperature is evident from these calculations. In arriving at the above estimates of time, the Ontario Hydro researchers assumed that the temperature at the contact interface would be close to the bulk temperature of the terminals. This assumption may not be justified; unfortunately, there are insufficient scientific data to establish clearly the temperature of the contact a-spots.

e.   Miscellaneous Investigations on Torque and Thermal Insulation. Contact pressure is known to be a critical parameter in the life of a wire connector for both copper and aluminum conductors. Ontario Hydro conducted a study to determine the effect of installation torque on connector performance (Ontario Hydro Research Report 78-155-K). Some salient findings of this study and the conclusions drawn by the Commission are summarized below.

The test procedures adopted were similar to other Ontario Hydro heat-cycle studies (i.e., a current of 27.5 amperes for $3^{1}/_{2}$ hours on and 1/2 hour off). For the number of pigtail and receptacle connections tested with both aluminum and copper conductors, the test life may be described by a relationship of the form:

$$\text{Test life (cycles)} \propto \text{torque}^x \qquad (32)$$

where the exponent x had the following values:

x = 3.6 for pre-CO/ALR receptacles connected to aluminum wire

x = 3 for pigtail connectors joining solid-aluminum conductors to extra-flexible copper conductor (41 strands)

x = 2.6 for pigtail connectors joining a solid-copper conductor to an extra-flexible copper conductor (41 strands)

At very low torques ($\sim$0.1 Nm), the results were perhaps not as reliable, since connections at these low torque levels operated at high temperatures and failed in a fraction of a cycle (in minutes). This study confirmed the previous observation (as noted in 2.6.3 *c.*) that copper-to-copper pigtail connections may last 100 times longer than those involving aluminum conductors under identical test conditions.

Many households in Ontario are resorting to blown urea-formaldehyde-foam thermal insulation to reduce the home-heating costs. When this form of insulation is applied, it is very likely that receptacle and other outlet boxes on the outside wall of a house would be filled with the foam

insulation. In a study, Ontario Hydro has endeavoured to estimate the corrosive effect of the foam insulation on wiring devices (Ontario Hydro Research Report 77-100-H). The researchers concluded that, although the foam insulation did cause surface corrosion of zinc-plated metal parts, it did not affect seriously the electric performance during a 28-day humidity exposure.

In another study (Ontario Hydro Research Report 78-96-K) involving the effect of additional thermal insulation (cellulose fibre, glass fibre, and urea-formaldehyde foam) on knob-and-tube wiring in Ontario homes, the Ontario Hydro researchers concluded that the additional insulation caused no problems from either overheating of electric conductors or connections or from deterioration of electric insulation. High-humidity exposure of the wiring with the additional insulation did not affect the wiring system adversely. However, the researchers urged that additional studies be conducted to assess:

1. The fire hazard resulting from embedding bare sections of knob and tube wiring in flammable thermal insulations such as cellulose fibre and polystyrene beads, and
2. The long-term performance of knob and tube wiring in an insulated stud space following exposure to a cycling environment representative of attic conditions.

2.6.4 National Bureau of Standards and Consumer Product Safety Commission of the United States

The Consumer Product Safety Commission of the United States came into existence in 1973 and soon after its inception it started an investigation of aluminum branch-circuit wiring. Since 1974, the United States National Bureau of Standards, as technical advisors to the Consumer Product Safety Commission, has done considerable laboratory work and field investigations on the subject of aluminum wiring. This section summarizes the information gathered from the publicly available documents.

In reviewing this information it should be realized that the residential-wiring practice in the United States differs in some aspects from that in Ontario. The main differences lie in the more frequent use in the United States of 20-ampere circuits, the use of steel screws, and the organization of the electrical-inspection services. A 20-ampere circuit would require a larger conductor size (AWG-12 copper or AWG-10 aluminum); this type of circuit is permitted in Ontario but is not used frequently. Steel screws for line conductors were never permitted in Ontario but an unspecified number of receptacles with steel screws reached the Ontario market and were installed in Ontario homes. Unlike that in Ontario, electrical inspection in most areas in the United States is the responsibility of local municipalities.

In preparing this section the Commission's technical staff has consulted the following reports:
1. National Bureau of Standards Reports NBSIR 75-723, NBSIR 75-672, NBSIR 75-677, NBS BSS-63, NBSIR 76-1011, NBSIR 76-1039, NBSIR 76-1184, and the various progress reports and memoranda pertaining to the Consumer Product Safety Commission Project 12.
2. Consumer Product Safety Commission Report (NIIC-0600-75-H006) by Rae Newman.
3. Consumer Product Safety Commission Pleadings File for CPSC v. The Anaconda Co. et al., 77-1843, before the United States Federal District Court for the District of Columbia, in Washington, D.C. This pleadings file contains several technical reports on the subject of aluminum wiring.

a. Field Surveys in the United States. As mentioned in Section 2.6.1, the Underwriters' Laboratories, Inc. was the first organization to conduct field surveys of difficulties encountered with aluminum building wire. The desirability of performing technical field investigations is underscored by limitations inherent in laboratory experiments, since there is a strong tendency in a laboratory to minimize the number of variables and to restrict the investigation to the examination of only a few of the relevant conditions. A carefully executed study of the interactions between performance parameters of various devices under field conditions is necessary. The information obtained from the field provides the basis for the definition of the necessarily limited scope of the laboratory studies.

The results of the surveys done in 1969, 1972, and 1974 under the sponsorship of the Underwriters' Laboratories, Inc. were examined critically by the National Bureau of Standards (Report NBSIR 75-677). The report concluded that these field-survey data should be used only as a collection of anecdotes from the field and that the available data lacked the characteristics necessary to develop a statistically sound estimate of the level of hazard associated with aluminum wiring. "Although the data do not establish statistically that there is a significant hazard, no more do they establish that there is not a hazard. There is, of course, ample evidence to *suggest* that there is a substantial hazard, but actual experience with the performance of aluminum wiring has varied widely."

Two further surveys in the United States are worth noting. In a 1975 study, military-personnel residences on 14 military bases were surveyed in order to estimate the extent of problems observed with aluminum branch-circuit wiring (Report NBSIR 76-1184). About seven of the bases reported problems within a normal limit, and the remaining bases experienced problems with 5% to 35% of the dwelling units. (Further information on this survey is included in Section 2.7.3.) Once again these data should be regarded as only anecdotal.

In 1977 the Consumer Product Safety Commission of the United States conducted a pilot statistical survey in Montgomery County, Maryland. A report on this investigation forms part of the pleadings file for CPSC v. The Anaconda Co. et al., 77-1843, before the United States Federal District Court for the District of Columbia, in Washington, D.C. The type of branch-circuit system was identified in a random sample of 200 homes selected from listings of building permits issued in Montgomery County, Maryland. Approximately 24% of the homes had aluminum wiring in all or a portion of the branch circuits, and 76% had all-copper branch circuits. During this survey, occupants reported that, prior to the investigation, duplex receptacles had been replaced — because of overheating or malfunction — in 26% of the aluminum-wired homes compared to 3% of the copper-wired homes. All repairs or replacements in copper-wired circuits were to receptacles of the push-in type.

Thermal measurements were made in 124 homes selected to represent four types of wiring systems:
1. Thirty-nine aluminum-wired homes with pre-CO/ALR duplex receptacles and one 20-ampere and two 15-ampere circuits.
2. Twenty-six copper-wired homes with pre-CO/ALR duplex receptacles and one 20-ampere and two 15-ampere circuits.
3. Thirty-one copper-wired homes with push-in duplex receptacles and one 20-ampere and two 15-ampere circuits.
4. Twenty-eight homes with both aluminum- and copper-wired circuits. Measurements were taken on one 20-ampere copper-wired circuit with either pre-CO/ALR binding-head screw or push-in types of receptacles and two 15-ampere aluminum-wired circuits with pre-CO/ALR duplex receptacles with binding-head screws.

Failure rates were based upon the percentage of homes in which at least one receptacle overheated after testing three circuits for 30 minutes at a load of 75% to 80% of the circuit rating. Seven of the 39 homes (18%) with 15- and 20-ampere aluminum circuits had at least one receptacle reaching 100°C., while this level of overheating was not found in any of the 57 homes with 15- and 20-ampere copper circuits. Failures occurred in both 15- and 20-ampere aluminum-wired circuits. In this thermal test no failures were recorded for copper-wired circuits using binding-head screw terminations. The data indicated poor workmanship more frequently on aluminum-wired receptacles than on copper-wired receptacles. Of the 31 aluminum-wired receptacles that reached 75°C. or higher during thermal testing, the terminal that overheated had poor wiring in seven cases and loose screws in two cases; poor workmanship was not indicated as a factor in 22 of the receptacles.

Receptacles that had reached a temperature of 75°C. or higher in this study were removed with wiring intact for examination by the Wright Malta Corporation, of Ballston Spa, New York. These aluminum-wired receptacles were subjected to simulated domestic-installation conditions, and detailed observations were made of possible fire-hazard conditions. The results are contained in Wright Malta Report CPSC-C-76-0115 (1977), which was included in the pleadings file referred to above. Of the 36 aluminum-wired devices installed in a laboratory test wall and subjected to a

load of 15 amperes, five devices started fires and nine others were considered hazardous.

Additional tests were done to establish the level of power dissipation needed at a receptacle terminal, wired with aluminum conductors in a typical domestic installation, to pose a fire hazard. The researchers concluded:

(i) A fire hazard exists when a duplex outlet device dissipates in the range of 10 to 20 watts and flammable materials such as wood chips, splinters, dust, or wall paper are in contact with the power dissipating terminal or adjacent wire.

(ii) At above 20 watts, temperatures are reached outside the box and on the face plate which create a fire hazard under many common household situations.

(iii) The power-on time required to achieve hazardous temperatures is within the on-cycle time expected of many household appliances, such as air conditioners, heaters, humidifiers, refrigerators, portable dishwashers, and others which are commonly plugged into branch circuits.

Power-dissipation measurements on aluminum- and copper-wired devices showed little variation from day to day on the copper-wired devices and widely from day to day on aluminum-wired devices.

The Consumer Product Safety Commission has sponsored theoretical heat-transfer studies involving pre-CO/ALR steel binding-head screw receptacles (Report CPSC-C-76-0116, included in the pleadings file noted above). These studies discuss the causes of overheating of aluminum wire terminations under steel binding-head screws in pre-CO/ALR devices. Again, it should be pointed out that in Ontario steel screws were never approved for current-carrying terminals but that an undetermined number of such devices may exist in Ontario homes. A summary of the major conclusions of these studies follows:

The major factor leading to reduction of contact pressures and loosening of aluminum wire under a steel binding-head screw was said to be the large difference in the linear coefficients of thermal expansion between aluminum and steel. In laboratory studies, a refined heat-transfer analysis showed that temperatures high enough to constitute a fire hazard could develop along aluminum wires from energy inputs at binding-head screw terminations. Five sets of conditions and assumptions were considered representative of processes that took place in the normal use of overheating receptacles. The calculations showed that temperatures at, or in excess of, self-ignition temperatures of common household materials were produced at the steel screw head, at the aluminum wire 1 inch away from the screw head, and at the side of the receptacle housing nearest the overheating terminal.

The Consumer Product Safety Commission is conducting similar field surveys and associated laboratory studies in other regions of the United States. The results of these surveys are not yet available to the general public.

b. Laboratory Studies at the U.S. National Bureau of Standards. Three departments of the National Bureau of Standards, in Washington, D.C., have been active in laboratory studies relating to aluminum-wiring terminations in residential circuits, namely, Technical Analysis Division, Center for Building Technology, and Measurement Engineering Division. In the main, external sponsorship for this work has come from the Consumer Product Safety Commission of the United States, but limited support has come from the Tri-Services Committee on Building Materials, the U.S. Department of Defense, and the Project Breakthrough of the U.S. Department of Housing and Urban Development. The main findings of these laboratory studies are summarized in the sections that follow.

(i) Resistance Measurements. Seven types of CO/ALR and seven types of pre-CO/ALR receptacles were compared for their connection resistance to AWG-12 aluminum wire. The binding-head screws (mostly of steel for pre-CO/ALR devices and of brass for CO/ALR devices) were tightened to 6 lb-in. A known test current from a low voltage source was passed through the receptacles. In some experiments copper-wired AWG-14 receptacles were compared with similar aluminum-wired circuits. From these data the Commission has made the following observations:

1. CO/ALR receptacles provided consistently lower connection resistances than pre-CO/ALR devices.

2. For all receptacles (CO/ALR and pre-CO/ALR), the resistance of the break-off tab was

either equal to or greater than that of the screw terminations. Moreover, the break-off tab resistance varied considerably from device to device. It was clear that the break-off tab contributed significantly (about 17°C. in some experiments with a CO/ALR device at a current of 40 amperes) to the temperature of the terminals. Of the devices tested, a CO/ALR device with a copper-contact assembly had the lowest tab resistance (0.05 milliohm). A pre-CO/ALR device (0.95 milliohm) and a particular CO/ALR device (0.55 milliohm) had the highest resistances.

The initial connection resistance for four types of CO/ALR and two types of pre-CO/ALR receptacles, with steel screws, was measured for torque levels from 2 lb-in to 20 lb-in for both copper (AWG-14) and aluminum (AWG-12) conductors. The resistance of the break-off tab was included in these measurements. The wire was formed into a planar 3/4 loop in all cases.

There was little variation between aluminum and copper conductors when connected to CO/ALR receptacles. For one sample with aluminum wire, the resistance decreased from 0.35 milliohm at 2 lb-in to 0.27 milliohm at 6 lb-in and then decreased gradually to 0.25 milliohm at 16 lb-in. For another CO/ALR sample with aluminum wire, the resistance at 2 lb-in was 0.65 milliohm, reducing to 0.57 milliohm at 6 lb-in and 0.54 milliohm at 16 lb-in.

The results for pre-CO/ALR devices were more dependent upon the initial torque and the resistance of copper-wired receptacles at most torques (≤ 12 lb-in) was lower than of those wired with aluminum conductors. This difference is more noticeable in receptacles with steel screws than in those with brass screws, as shown in Table 35.

Table 35

RESISTANCE VERSUS TORQUE

Torque lb-in	Brass Screw		Steel Screw	
	Aluminum	Copper	Aluminum	Copper
2	1.83	0.83	2.06	1.30
6	0.88	0.72	1.21	0.89
10	0.75	0.68	1.02	0.80
14	0.67	0.66	0.86	0.69

Resistance values are in milliohms. Post-1972 Aluminum-alloy material was used.

Experiments were also done to establish the distribution of current in a typical binding-head screw connection by measuring the following resistances:

R_1 = wire-to-plate
R_2 = wire-to-screw
R_3 = screw-to-plate
R_n = total connection resistance

In these tests it was found that the path resistance from wire to plate (R_1) was from three to five times greater than for the path through the screw ($R_2 + R_3$). As a result, 75% to 80% of the current was carried through the screw instead of directly from the wire to the plate. In one experiment with a pre-CO/ALR receptacle, the current path through the screw was deliberately blocked. This resulted in a temperature of 174°C. at the terminal within 15 minutes when a current of 40 amperes was passed through the connection. On both CO/ALR receptacles the resistance (R_1) was substantially greater than ($R_2 + R_3$). Moreover, the resistance (R_1) appeared to be more sensitive to the initial screw torque. The main reason for this appeared to be the cutting and scraping action of the undercut screw head. Compared to an aluminum-wired connection, a copper-wired connection provided substantially lower wire-to-plate resistance (R_1), whereas the other two resistances (R_2 and R_3) appeared to be essentially similar for both conductor materials.

These experiments may also help to explain the erratic behaviour of aluminum-wired connections at low torque levels since the interfaces involved in the wire-to-screw-to-plate connection are likely to be more susceptible to vibration and sudden shocks.

(ii) Post-Installation Torque Tests. Two types of pre-CO/ALR and seven types of CO/ALR receptacles were tested with AWG-10 aluminum wire to establish the effect of pushing a wired receptacle back into the outlet box. Three torque levels were selected: 6, 10, and 14 lb-in. On both pre-CO/ALR devices tested, the measured post-installation torque was variable, particularly at the 6 lb-in and 10 lb-in levels. At 6 lb-in, one of the 24 test connections was totally loose and 11 had residual torques of less than 3 lb-in. At the 14 lb-in test level, the post-installation torques ranged from 10.4 to 10.6 lb-in. CO/ALR receptacles, on the other hand, performed better: in a total of 60 tests, there were no totally loose connections. Even the poorest performer had an average residual torque of 4.3 lb-in. At the test torque level of 14 lb-in, the average residual torque was between 13 and 13.5 lb-in.

(iii) Current and Heat-Cycle Tests. Researchers used several different current cycles to accelerate failure mechanisms in residential-wiring terminations. For example, in one case the current cycle consisted of 12 minutes on and 6 minutes off at 40 amperes. The present CO/ALR current-cycle test calls for an on period of $3^1/_2$ hours followed by an off period of 1/2 hour. In both these cycles the current is derived from a low voltage (4 to 6 volts) source. Researchers at the National Bureau of Standards also experimented with power cycles, when the current was taken from a 115-volt source.

A cycle of 12 minutes on and 6 minutes off does not permit a complete thermal equilibrium to be established. Power cycles tend to produce, in some cases, a little higher temperature (2°C. to 5°C.) than current cycles from low voltage sources. Some researchers believe that a lower current (22 amperes) should be used in an insulated wall, because high currents (40 to 53 amperes) tend to anneal the wire and thus make the tests a little less onerous. Also, perhaps longer cycle times — of 10,000 to 15,000 hours — are needed to bring out degradation rather than the 2,000-hour test period specified in the CO/ALR tests.

The ambient temperature for the current-cycle tests can also have a significant effect on the results. It is believed that environmental conditions in homes without air conditioning may result in wall temperatures higher than 30°C.

The present CO/ALR tests do not simulate other mechanical stresses, such as an impact blow, which may be more severe than the wire-disturbance test specified in the CO/ALR tests. Similarly, the vibration transmitted from appliances connected to a receptacle is not simulated in the existing test programmes.

In one experiment 10 pre-CO/ALR receptacles with steel screws were wired with pre-1972 AWG-12 aluminum conductors (which is likely to be a common EC-grade wire), and the screws were tightened to 6 lb-in. The current cycle selected was 12 minutes on and 6 minutes off at 40 amperes. After 4,800 cycles two of the screws on the live side in one receptacle reached approximately 150°C. From the data on this test the researchers made the following observations:

1. The interface resistance between the wire and the plate (R_1) was highly erratic; it could vary several orders of magnitude both initially and during cycling. The average wire-to-plate resistance reached a value of 13 milliohms.
2. The interface resistance between the wire and screw (R_2) did not behave so erratically. In most connections, however, this resistance did increase measurably with cycling. After 4,300 cycles this resistance on the average was 0.24 milliohm.
3. The resistance between the screw and the plate (R_3) appeared to fluctuate more and was generally higher than (R_2). On two terminals this resistance rose dramatically, which caused substantial temperature rise. The average value of (R_3) after 4,300 cycles rose to 0.66 milliohm.

To compare the effect of heat cycling versus current cycling, several pre-CO/ALR receptacles were wired as in the above tests but were subjected to temperature cycling, without a current, by blowing hot- and cold-air streams ($1^1/_4$ minutes hot, $2^3/_4$ minutes cold). The temperature excursion achieved in this manner was 65°C. (35°C. to 100°C.) every 4 minutes. Periodically the cycling was stopped to measure the various interface resistances. After 9,255 cycles, three out of a total of 32 connections exhibited a substantial rise in resistance. For example, total termination resistances of 0.91, 0.96, and 0.98 milliohm increased to 1.7, 2.5, and 3.7 milliohms, respectively. If these connections had been subjected to a current of 40 amperes, overheating

would have resulted. A comparison of the current-cycle and heat-cycle tests revealed similar behaviour. It appears that the wire-to-plate current path became ineffective very rapidly, thus forcing the termination performance to be entirely dependent upon wire-to-screw and screw-to-plate interfaces.

(iv) Current Cycling Tests in Simulated Wall Installations. The National Bureau of Standards Report NBSIR 76-1184 gives details of an exhaustive study comparing pre-CO/ALR and CO/ALR receptacles connected to AWG-12 copper wire and AWG-10 aluminum wire. All the receptacles were installed in an insulated wall. The aluminum alloy was of the post-1972 variety, i.e., it is likely to be comparable to the aluminum-alloy conductor material (ACM) in Ontario. Two types of pre-CO/ALR receptacles, one with zinc-plated steel screws and the other with brass screws, and four types of CO/ALR receptacles were used in these tests. Insulation torque levels from 2 lb-in to 20 lb-in were investigated. A current of 15 amperes was cycled for 3½ hours on and 1/2 hour off. For purposes of comparison, overheating was defined as a temperature of 10°C. or more above the average third-cycle temperature. Overheating of aluminum-wired receptacles was observed in some circuits with pre-CO/ALR devices at screw torque levels of between 2 lb-in and 6 lb-in. Aluminum-wired non-CO/ALR receptacles did not overheat at a torque level of 12 lb-in or more. Copper-wired non-CO/ALR receptacles showed no sign of overheating, regardless of torque level (less than 2 lb-in). Several other observations may be made from this series of tests:

1. The average third-cycle temperature for zinc-plated steel screws on pre-CO/ALR devices wired with aluminum was 55°C.; the equivalent temperature for brass screws was 59°C. At higher torques (∼12 lb-in) there was no noticeable difference between steel- and brass-screw devices.
2. The average temperatures for copper-wired pre-CO/ALR receptacles, with steel and brass screws, were slightly lower than those for aluminum conductors.
3. CO/ALR receptacles wired with AWG-10 aluminum conductors ran appreciably cooler (∼33°C.).

(v) Long-Term Cycling with CO/ALR Receptacles. In April 1975 the National Bureau of Standards initiated a current-cycling test with CO/ALR receptacles. A current of 40 amperes with a cycling period of 20 minutes on and 10 minutes off was selected. AWG-12 aluminum-alloy conductor material was used to wire five samples of each of six different types of CO/ALR receptacles. All the samples had indium platings and some of the samples were aged artificially to simulate shelf life. The test results, after approximately 33,000 cycles (i.e., over a two-year period), indicated that:

1. There was little difference in temperature of new and aged devices. This seemed to indicate that a shelf life of five years should have little or no effect on performance at normal temperatures.
   The researchers knew of no way of relating such a test to the normal life of a device but considered this test as extremely severe.
2. Only one terminal failed, but this was considered a freak incident.

(vi) Glow Phenomena with Pre-CO/ALR Receptacles. In 1976 the National Bureau of Standards issued the Report NBSIR 76-1011 on arcing phenomena observed in pre-CO/ALR receptacles when the electric terminations were loose. During laboratory tests, visible glows were observed in normal 120-volt, 15- and 20-ampere residential branch circuits wired with both copper and aluminum.

Glowing terminations may waste up to 35 watts of power with a current of 15 amperes and about 5 watts when the circuit current is 0.8 ampere. Very high temperatures (∼400°C.) were measured at the break-off tab in some receptacles, and metal outlet boxes, each with a glowing connection, may reach temperatures approaching 175°C. Laboratory tests showed that a receptacle's steel binding-head screw connection, exposed to the air, sustained glow conditions for over 100 hours under repeated, periodic, and on/off cycles of load. The electric performance of fixtures, appliances, or other electric loads is not noticeably affected by glowing terminations, nor will they cause the overcurrent-protection devices to operate. It appeared that vibra-

tion or disturbance (for example, by insertion or removal of an attachment plug) of a loose contact was the most common mode of initiating such glows. ''Glows were established and sustained for at least five minutes at the interface between the following materials.

1. Copper wire and steel block
2. Aluminum wire and steel block
3. Copper wire and aluminum wire
4. Copper wire and copper wire
5. Aluminum wire and aluminum wire

With repeated attempts glows were not established between either copper wire and brass blocks or between aluminum wire and brass blocks. . . . Repetitive arcing will readily continue'' for the above material combinations or for aluminum or copper wire against brass blocks while there is a motion at the interface. ''After the disturbance ceased, electrical and temperature measurements indicated that either an open circuit or a relatively good contact existed.''

Reports of a meeting, which was held in New York on March 31, 1977, under the sponsorship of the Underwriters' Laboratories, Inc., were provided to the Commission by UL. These reports indicated that there was conflicting experimental evidence from other sources on the glow phenomena.

Clearly, the scientific explanations for glow phenomena are not well understood, and further experiments and analysis obviously are required.

(vii) Effect of Current Transients. Tests were conducted with a load of a bank of incandescent lamps and an air conditioner supplied through a series of pre-CO/ALR and CO/ALR receptacles. A peak current of 155 amperes was possible with the lamp load. The current transients did not appear to have had any deleterious effects on the receptacle performance.

(viii) Salt-Spray Corrosion Studies. The National Bureau of Standards performed a series of tests to compare the performance of terminations made with aluminum, copper, and copper-clad aluminum conductors that were wired to steel or brass binding-head screws during exposure to a laboratory salt-spray atmosphere (Fourth Quarterly Report, CPSC Project 12, October, 1974). The results indicated that connections made with AWG-10 aluminum conductors under either brass or steel binding-head screws were more susceptible to corrosion (as evidenced by a change in termination resistance) than connections made with either copper or copper-clad aluminum conductors.

(ix) Indium Diffusion on CO/ALR Receptacles. In studies conducted at the Bell Laboratories of the United States (Barnard, 1974), it was shown that indium interdiffuses readily with copper and brass and forms brittle intermetallics. Since several of the approved CO/ALR receptacles utilized an indium coating, this effect was investigated by the National Bureau of Standards.

Two CO/ALR receptacles, wired with an AWG-10 aluminum conductor, were subjected to a current-cycle test at 53 amperes with a cycle of $3\frac{1}{2}$ hours on and 1/2 hour off. One of the receptacles was subjected to approximately 5,000 cycles. Metallographic examination revealed that the indium plating did convert to the indium-brass intermetallics. The electric performance of the terminations did not appear to deteriorate significantly under a low-voltage current-cycling test. However, under the power-cycle tests, some proof of higher temperatures at the terminals was given by the discoloration of the wire insulation. In additional tests termination failures occurred with CO/ALR receptacles which had been heat-aged prior to being wired and subjected to current cycles.

In a recent study (General Electric Company Report 76CRD124, June 1976), A.W. Urquhart studied the differences between indium and tin platings on copper-alloy substrata. His findings indicated that, in general, tin platings reacted more slowly than the indium platings, with or without the presence of a nickel-plated barrier layer adjacent to the substrata. The parabolic-rate constant for tin is two times lower than that for indium. In one indium-nickel specimen it was observed that nickel tended to diffuse preferentially along indium grain boundaries, ahead of the reaction-product layer.
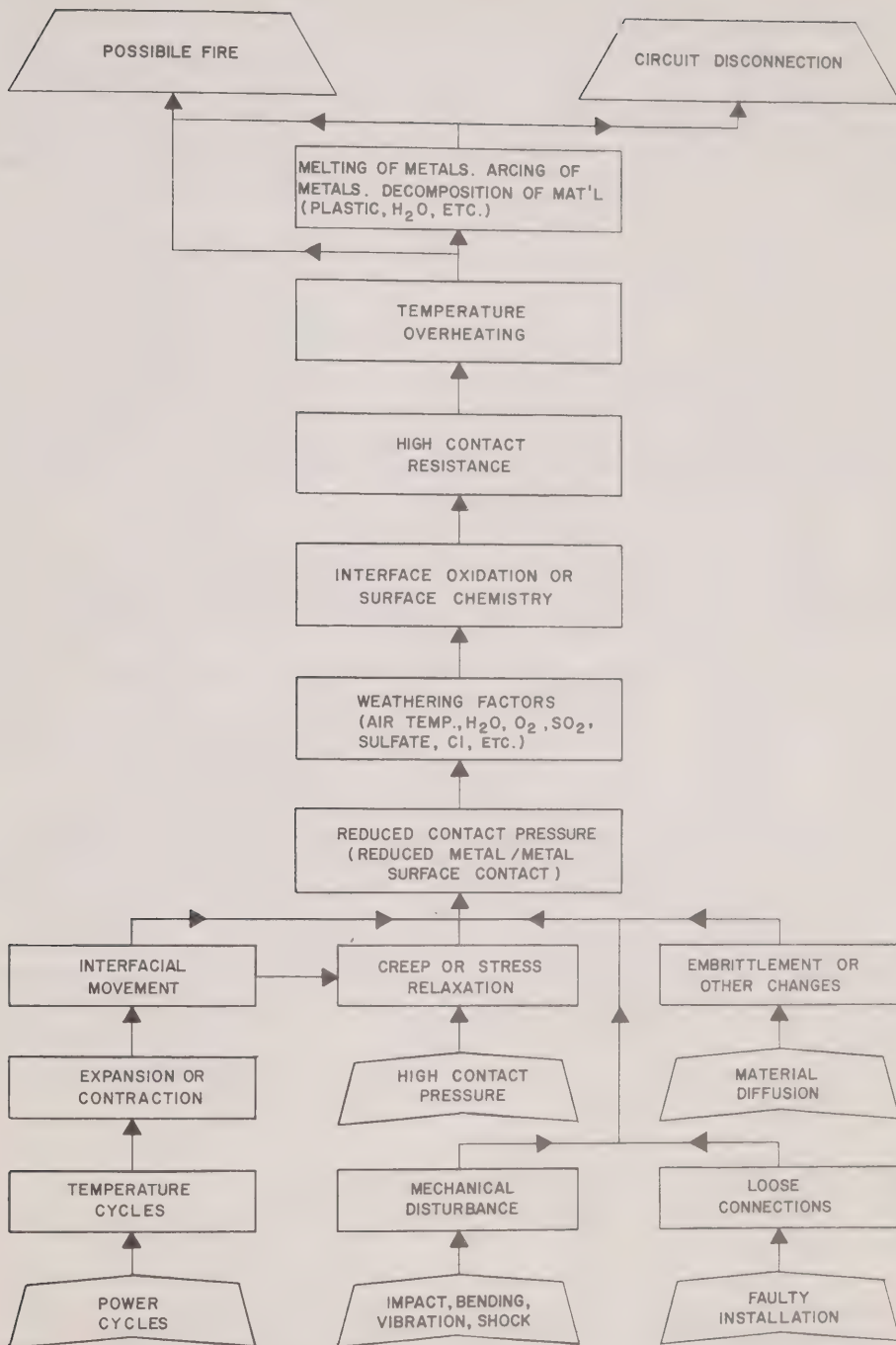
Figure 55. Preliminary Identification of Possible Failure Mechanisms

The implications of these metallurgical findings on the long-term performance of CO/ALR receptacles are not fully understood.

(x) Compressive-Creep and Stress-Relaxation Measurements for Loops of Aluminum and Copper Conductors. During 1974 and 1975 the Metallurgy Division of the National Bureau of Standards conducted creep and relaxation measurements, in the transverse direction, on four aluminum-alloy conductors and one copper conductor. The wires tested were AWG-12 and the tests were done at room temperature and at 100°C. The creep test loads were 60, 196, and 300 pounds and the observation period was one week. The findings of this investigation may be summarized thus:

The relaxations of the copper alloy occurred at a rate slower than its creep, whereas all the aluminum alloys tested exhibited opposite behaviour, i.e., their creep rate was slower than the relaxation rate.

One of the aluminum alloys, identified as Type B, and the copper alloy were clearly superior in both creep resistance and resistance to stress relaxation. This was a surprising result since copper has the highest hardness and the highest yield point, whereas the Type B aluminum alloy is one of the softest and has the lowest yield point. Type C alloy was very close in hardness and yield to Type B but had far worse creep and relaxation properties. These results clearly pointed out the error in inferring creep and relaxation behaviour from simple mechanical properties, such as hardness and yield point.

(xi) Novel Approaches to Residential Branch-Circuit Wiring Terminations. The National Bureau of Standards has considered new techniques for making residential branch-circuit wiring terminations. Reports NBSIR 75-672, NBS BSS-63, NBSIR 76-1039, and Value Engineering Report on Contract no. CPSC 76-22-5200 deal with novel approaches to residential branch-circuit wiring.

Two techniques of using compression connections are discussed in Reports NBSIR-76-1039 and CPSC 76-22-5200. Five currently available compression connectors were evaluated in heat-cycle tests and some were found to be suitable for branch-circuit applications with aluminum wire. In 1977, the Consumer Product Safety Commission sponsored a few pilot installations using these compression connections for retrofitting houses in the United States. The techniques and the problems encountered are discussed in Report CPSC 76-22-5200, prepared by the Value Engineering Laboratory, of Alexandria, Virginia. In other documents (the Consumer Product Safety Commission Memoranda BESDOC 521015 and 520560), the overall rationale for introducing compression connections into residential branch-circuit wiring was explained. From these reports and documents it is clear that such connections are technically sound and have been in use for larger-sized conductors for a long time. Misuse of such a system by a home handyman was also discussed. It was also recognized that a compatible system of lugs and tools, acceptable to the residential-wiring industry, was not yet available commercially but could be developed easily given time and encouragement.

(xii) Failure Mechanisms. The complexity of the failure mechanisms in residential branch-circuit wiring terminations is apparent from the flow diagram shown in Figure 55.

2.6.5 Summary of Research at Battelle Columbus Laboratories

Information in this section is quoted from the National Bureau of Standards Report NBSIR 75-723.

   a.   *Origin, Scope, and Purpose of Study.* In June 1971, a research program on connections for aluminum wire and cable was initiated at the Battelle Institute in Columbus, Ohio. Support for the program was obtained from a number of U.S. and foreign companies including aluminum wire and cable manufacturers, wiring device and connector manufacturers and other manufacturers and users of electrical equipment which may be used with aluminum wire.

   The purpose of the study has been to define the failure mechanisms and to conduct a reliability analysis of aluminum terminations.

   The scope of the program includes solid and multistrand aluminum conductors ranging from circuit sizes down to communications-size wire. Termination types included in the study are crimp, clamp, binding head screw and set screw.

b. Cyclic Performance Tests. Battelle has utilized a power cycle test to study the performance of electrical components. The test consists of passing currents of 40 or 53 amperes (depending on the wire size) through wired devices in cycles of 12 minutes ON and 6 minutes OFF. The device temperature, as measured by a thermocouple installed on the break-off tab, is monitored during the test. The connector devices are installed in open air during the tests and a torque of 6 in-lb is used. The criterion for failure is based upon an increase in the device temperature. Based upon laboratory studies, Battelle believes that a 10°C rise in device temperature is sufficient indication that substantial overheating is imminent. Therefore, a 10°C rise in temperature is used as the criterion for failure.

Most of the Battelle cyclic test data has been obtained using one type of receptacle and they question the reliability of extrapolating the data to other devices.

c. Chemical and Mechanical Properties of Aluminum Alloys. Numerous alloys of aluminum have been studied in the program including both "old" and "new" technology wire. The alloys were analyzed for chemical composition using optical emission spectroscopy and for various mechanical properties such as ultimate tensile strength, yield strength, elongation, elastic modulus, thermal stability, tensile creep and stress relaxation.

An attempt was made to correlate tensile creep and stress relaxation results. It was found that correlations between these results were poor. Battelle found that the optimum wire properties with respect to low stress relaxation are 1) low tensile creep, 2) small stress dependency for creep, and 3) as low a yield stress as practical.

Battelle reports that, for EC-grade aluminum ("old") technology wire, stress relaxation at room temperature can result in substantial loss of metal-to-metal contact between the wire and the screw or connector plate in a relatively short time. However, for aluminum-alloy conductor ("new") technology materials, there is no viable mechanism based on stress relaxation to account for substantial screw loosening. They also report that no correlation has been found between any measurable mechanical property and termination performance.

d. Effect of Screw Material and Torque on Failure Rate. Studies were conducted with steel, brass and aluminum binding head screws with various metallic platings. Zinc was *not* recommended as a plating material because of its susceptibility to oxidation and its general metallurgical incompatibility with aluminum. It was also found that the screw material may have the greatest influence on the termination reliability. The termination failure rates were lowest with aluminum screws and highest with steel screws.

The studies have shown that increasing the torque of the binding head screw does not improve the initial contact resistance significantly; however, it can increase the life expectancy substantially.

e. Failure Mechanism. The studies to date have led Battelle to conclude that microscopically small motion occurring at the termination point is the prime factor in leading to overheated terminals. The same mechanisms are thought to apply to both copper and aluminum wire although they can and do occur at different rates. As a result of the motion, a wear or fretting process occurs which gradually destroys the metal to metal contact by the formation of an oxide film at the interface. The oxide is a path of high resistance and results in overheating at the interface. The motion presumably can be due to thermal expansion and contraction although Battelle does not specifically say this.

In distinguishing between copper and aluminum wire, Battelle believes that aluminum is less forgiving of motion than copper and that a higher force must be maintained in an aluminum wired system to prevent motion or to escape the consequences of it. The studies show that if motion occurs, failure will occur in the following order: bare aluminum first, nickel plated aluminum second and copper or copper-clad aluminum third.

Battelle believes that connector devices designed to prevent motion would substantially reduce the possibility of failed (overheated) terminations.

f. Prediction of Long-Term Performance. Battelle has applied the Arrhenius time-temperature equation to predict the long-term performance of connectors from short-term test results. Basically, the process involves determining the *rate* of degradation at several elevated temperatures and extrapolating the rate curve to the desired (lower) service temperature. The rate of degradation is greater at elevated temperature than at the service temperature so that, presumably, long-term performance can be predicted in a much shorter time than would be required at the service temperature. By applying the Arrhenius relationship to the results of power cycle tests, Battelle has predicted lifetimes for various wire alloys and other components.

The reports emphasize, however, that the Arrhenius analyses do not include factors such as loose screw connections, wire disturbance or motion which could accelerate the degradation substantially.

The studies show that the failure rate is extremely sensitive to temperature and that the ambient air temperature may have a very significant effect on the test results. Battelle believes that testing specifications should be based on the temperature of a standard control device rather than on current because of the rate dependence on temperature.

g.   Indium Plating. Conventional connector devices were modified by plating with indium. The indium platings varied in thickness from 0.2 mil to 1.0 mil. Both side wire and push wire devices were plated.

With the indium plated side wire device, excellent temperature stability was achieved at 40 to 50 ampere testing. At 50 amperes, 20°C temperature rise failures were observed, but thermal runaway conditions were not reached within 2000 cycles. Typically, a 20°C rise in temperature was followed by a sharp drop in the terminal temperature followed by a longer term stability or a later transient rise.

A push-in (push wire) receptacle, which in previous experiments would not function reliably with any available aluminum alloy, was modified with 0.2 and 1.0 mils of indium. During 1000 cycles, the push-in device exhibited stable performance within a 10°C temperature rise limit.

Thus, the indium plating was shown in these preliminary experiments to increase the performance of the devices by preventing thermal runaway.

Battelle reports, however, that indium diffuses with other metals such as copper. The diffusion process changes the characteristics of the indium but it is not yet known if the diffusion is deleterious to the connector performance.

h.   Push-in Devices. Battelle studies have shown that push-in devices perform poorly with bare aluminum wire.

i.   Twist-on Devices. Battelle has studied two typical twist-on (wire-nut) devices using two wire (Al-Al), two wire (Al-Cu), and three wire (Al-Cu-Al). The wire size was No. 12 AWG. The results have shown that the highest failure rates were obtained with the Al-Al, two wire connection when tested at 40 amperes. The Al-Cu two wire connection yielded the lowest failure rate of the twist-on connections tested.

The results indicate that the wire composition is a major factor in determining pigtail reliability. Battelle believes that the nature of the surface film on the wire is the dominant factor in leading to failure.

The tests that have been conducted show that only one type of aluminum wire with twist-ons has been able to survive the same type of cyclic test required for other parts of the electrical system. This aluminum wire has been shown to have a surface coating of MgO.

Battelle also conducted studies in which the steel springs of twist-ons were plated with indium. The results indicated a definite improvement in the performance of one type of twist-on. But the degree of improvement was not sufficient for reliable performance of more than one and possibly two additional aluminum alloys.

j.   CO/ALR Device. Preliminary tests with a commercially available CO/ALR device without indium plating and No. 10 EC aluminum wire at 6 in-lb torque have shown that a device temperature increase of 20°C can be obtained in less than 700 cycles if the Battelle wire disturbance is used. However, Battelle expresses concern that the wire disturbance test may be too stringent because old style devices with #12 copper wire at 6 in-lb also fail the test after one or two disturbances. Since a significant field failure rate with copper wired old style devices has not been identified, the wire disturbance test may not actually represent field conditions.

k.   Joint Compounds. Battelle has studied two joint compounds which are supposed to help reduce the termination problems with aluminum. The system chosen for evaluation was a worst case condition using a conventional device, EC-H 19 (high stress relaxation) wire with distorted loops, 6 in-lbs torque and 40 amperes.

The results showed that neither joint compound improved the initial quality of the connection or improved operating characteristics.

2.7 Experience with Safety and Reliability of Household Wiring

2.7.1 Hazards in the Home

Everyone expects modern homes to be safe and comfortable and is shocked when accidents occur. Unfortunately, the provision of comfort — in the form of light, heat, and the power required to operate a multitude of appliances — requires the introduction of combustible fuels and powerful electric systems which, by their natures, are hazardous and can, if not controlled, cause damage, injury, destruction, and death.

It is a tribute to the skill of the construction industry and to the effectiveness of building codes and inspection services that these hazards usually are controlled, and that homes generally are safe. Nevertheless, accidents and fires do happen and they happen much too often. It is right, therefore, that consumers be concerned and agitate for investigations into possible means of reducing the frequency of dangerous incidents.

The major cause of trouble is that the housing industry, an example of an advancing technology, is constantly introducing new materials and appliances and different methods. All of these innovations, before they are introduced, are carefully considered, tested, inspected, and licensed. It is easy to say that such a process *should* eliminate dangers, but it is an unfortunate commentary upon the fallibility of the human imagination and the lack of foresight that the history of all technologies is full of hazards and failures that conceivably might have been foreseen but, in fact, were not. It is particularly difficult to anticipate the possible interactions when several changes are introduced together.

Residential electric systems possibly would be safer and certainly would be understood more widely if they were visible, but few householders would accept this; as a result, wiring and its potential dangers are hidden behind walls. The concealment of wiring systems and the general ignorance of the public about their details mean that householders are often unaware of hazards that may exist in their homes.

One hazard that is not generally understood is that many receptacles are integral parts of a branch circuit, with electric current flowing through the receptacles even when they appear to be not in use. When a load is applied to a particular receptacle by connecting an appliance to it, the current path includes every receptacle or device between the panelboard and the receptacle in use. These receptacles and devices will thus be passing current even if they are not in use and may become hot whenever an appliance is operating further along the circuit.

Another hazard that is not sufficiently appreciated is that, when a receptacle or other wiring device overheats, the normal protective devices in residential circuits, fuses, and circuit breakers do not necessarily operate to isolate the faulty part. Fuses and circuit breakers in the panelboard of a residence are not affected by heat in a device in a remote part of the building. They do not operate unless an overcurrent condition is established simultaneously with the overheating, which is usually the case.

The Commission has no way of knowing how many householders have had or are having problems with residential aluminum wiring and are unaware of them. The evidence presented suggests that some householders who were experiencing problems were unaware of the cause until they read newspaper or heard broadcast reports, or learned of the problems from neighbours or friends. Because very few householders inquire about the nature of wiring in their homes — whether the house is acquired new or as a resale — and because problems can occur sometimes without the usual warning symptoms, it is likely that many families are unaware of the potential safety hazards that exist in their homes. This same lack of knowledge about household wiring has undoubtedly caused some householders to become apprehensive for no reason except that they have heard that hazards may exist but have no idea how to recognize them. The publicity given by the media has been useful in that it has alerted many householders to potential hazards, and

this had led in many cases towards their rectification. Other householders, who had observed signs that aroused their apprehension, unfortunately failed to take adequate precautionary measures.

One further problem concerning residential wiring should be mentioned. While there is no such thing as absolute safety, there are degrees of safety. For example, receptacles of a superior quality and considerably higher cost are installed in hospitals and certain other institutions. Householders could demand receptacles of similar quality for residential wiring, but the price of houses would be increased. At some stage in the designing of household wiring, as of many other manufactured goods, an engineer has to decide which grade of device, what degree of safety, and what price would best meet the needs of the public.

2.7.2   Safety Information

When a wiring device overheats or exhibits other forms of abnormal operational behaviour, the associated branch-circuit fuses or circuit breakers will operate automatically and isolate the circuit only when there is an overcurrent or faulty current condition at the same time. Fortunately, in most cases, the deterioration of the device to a hazardous level occurs slowly. During this degradation period, the abnormalities are accompanied by warning symptoms of which the householder may become conscious and, if so, can initiate remedial action. The warning symptoms normally are revealed by signs of heat, discoloration of the cover plates of devices (due to heating), release of odours, persistent flickering of lights, or intermittent operation of equipment for no apparent reason.

In 1975 the Electrical Inspection Department of Ontario Hydro, in response to inquiries by members of the public, prepared a safety-information card regarding aluminum-wiring systems (see Figure 56). It was intended to distribute the cards by either enclosing them with the electric-meter bill or handing them out at information centres in utility showrooms and service centres.

Four important facts about
ALUMINUM WIRING

- *Aluminum wiring is not a fire hazard* — although some overheating may occur at receptacles supplying heavy loads (refrigerator or air conditioning).

- *What to watch for:*—hot or discoloured cover plates on receptacles; unusual odours near receptacles; persistent flickering lights.

- *What to do:*—replace suspect receptacles with CSA Approved CO/ALR receptacles—and have this work done by a qualified electrical contractor. Have the finished job inspected.

- *Do you have aluminum wiring?* Homes built before 1968 will not have aluminum wiring unless additional circuits have been added since the house was built. And, not all new homes have aluminum wiring.

Your electrical inspector can give you further advice if you are still in doubt.

A safety message from your hydro
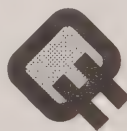
Figure 56.   Safety Information Card Prepared by Ontario Hydro.

The Commission heard evidence that the distribution of the card was limited, which may have been due to the facts that the information related only to aluminum wiring and that many utilities would have very few or no aluminum-wired homes within their service areas. This limited distribution is unfortunate, as the information regarding the kinds of symptoms warning of pending failure of aluminum-wired devices applies equally to copper-wired devices. The Commission was

not presented with evidence that any similar safety-information literature was issued for copper-wired systems. Presumably there was never a significant need to do so.

Safety information similar to that prepared by Ontario Hydro was reported by home-owner groups in their newsletters and other correspondence to their members. The following excerpt is from a form issued by a home-owners' group in Brampton (Exhibit 88):

THE SEVEN WARNING SIGNS

1. Wall outlets which cease to work or which become overheated or discoloured or emit strange burning odor.
2. Baseboard electric heaters which fail to function or emit strange burning odor or slow to heat.
3. Unusual burning odor from fuse panel or meter box
4. Fuses blow or circuit breakers trip frequently.
5. Appliances such as an iron, toaster, or waffle iron slow to heat.
6. Lights dim noticeably when appliances are operating.
7. The television picture shrinks or reception of television or radio is poor when appliances are in use.

If you are experiencing this problem, call your local Electrical utility and/or Ontario Hydro. If they fail to respond, call a qualified electrician to inspect your electrical system. Keep a record of the problem; i.e. burnt out receptacle or twist on connection, and maintain a record of your repair costs.

2.7.3 Householders' Experiences

Information on householders' experiences with residential aluminum wiring was collected by the Commission in several ways. First, some householders and members of the public wrote to the Commission, relating their experiences with aluminum wiring in their homes. Second, a home-owners' public-interest group, located in Brampton, provided the Commission with copies of letters that the group had received. Third, several home-owners gave testimony before the Commission in Toronto, Ottawa, Scarborough, and Brampton. Fourth, the Ontario Housing Corporation described to the Commission its experience with aluminum wiring in residential units under its jurisdiction. Finally, the Commission has studied most of the publicly available documents from the United States concerning householders' experiences with residential aluminum wiring.

a. Letters and Inquiries from the Public. The Commission received many letters written by members of the public, officials of municipalities, and members of other groups both within and outside of Ontario. Some letters were sent directly, and some had been sent to the Brampton home-owners' association. A number of people telephoned the Commission and sought advice from, or related some experience to, the Commission.

The observations below summarize the types of letters and telephone inquiries:

1. Various members of the public were concerned about unexpected or unusual problems with aluminum-wired systems in their homes.
2. Several people had experienced a fire, or a fire incident which had been controlled.
3. Some home-owners had difficulty finding electricians to execute satisfactory repairs.
4. Prospective home buyers asked whether a home wired with aluminum should be purchased.
5. Local fire-department or municipal officials inquired about whether they should restrict temporarily the use of aluminum wiring in houses being constructed.
6. Electrical contractors outlined their experience with the use of aluminum wiring.

The Commission is grateful to all of these people for taking the time to inform the Commission of their concerns and interests.

b. Home-Owners' Testimony at Hearings. At public hearings held by the Commission in Brampton, Toronto, Ottawa, and Scarborough, some 30 home-owners testified in person regarding their experiences with the wiring systems in their homes. The home-owners described the age of their homes, the type and number of rooms, the size of family, the source of energy used for comfort heating and for domestic hot-water heating and cooking, the number and types of electric-powered appliances, the nature of their experiences with the wiring system, the types of devices involved and their location in the house, the nature of remedial work undertaken, and

whether or not advice had been sought from the authorities.

The home-owners' oral testimony may be summarized as follows:

(i) Receptacle Connections. Eighty per cent of the witnesses testified that they had had problems with receptacle connections. The problems related to failures with steel-screw and push-in types of receptacles, among others. Twenty-eight per cent also testified that they had discovered receptacles with loose connections.

(ii) Pigtail Connections. Seventeen per cent testified that they had had problems with pigtail connectors, mostly related to the use of solid-aluminum and extra-flexible stranded-copper wire; usually the problem was with baseboard-heater or water-heater connections.

(iii) Panelboards. Ten per cent testified that they had had problems with panelboards. One witness described the problems he had encountered with blowing fuses. He commented that the fuses did not screw in very well and the panelboard bus bars had black marks and were indented where the fuses had made contact with them.

(iv) Disturbing Signs. Sixty-eight per cent testified that they had observed disturbing signs similar to such warning symptoms as overheating, odour, smoke, and noise.

(v) Incandescent-Lamp Failures. Seventeen per cent testified regarding problems with incandescent lamps which failed long before the normal expected lifetime. Some of the witnesses experienced trouble simultaneously with the light-fixture wiring connections, which may have had a detrimental influence on the lamps.

(vi) Flickering Lights. Thirty-eight per cent testified that they had experienced problems with flickering, dimming, and on/off or intermittent operation of lights. Several of these witnesses also experienced problems with receptacle connections.

(vii) Changes to CO/ALR. Thirty-five per cent testified that they had installed CO/ALR receptacles either to replace a defective receptacle or to generally upgrade their systems. Ten per cent changed to non-CO/ALR but some of these modifications were made prior to the introduction of CO/ALR devices.

(viii) Advice from Authorities. Fifty-six per cent testified that they had received advice from the authorities.

(ix) Branch-Circuit Wiring. All of the witnesses had aluminum-wired branch circuits. The electric baseboard-heating circuits of one witness were wired with copper but her 15-ampere, non-heating branch circuits were wired with aluminum.

(x) Incorrect Wiring. Nineteen per cent testified that they had experienced problems with incorrect wiring installations, although the installations had been inspected and approved. The problems included, among others, incorrect circuiting of lights, split receptacles, doorbell transformer, and the location of a receptacle in a kitchen cupboard.

(xi) Spare Capacity. Fifteen per cent testified that they had experienced problems in connecting additional circuits and loads to the panelboard. If sufficient spare circuits were not available in the panelboard, there were no convenient subfeed terminals from which to supply an additional panelboard.

(xii) Fires and Overheating. Several home-owners had experienced first-hand knowledge involving fires or potential fire hazards as a result of failing receptacles. The following are some examples of experiences encountered by witnesses.

Mr. W.L. Bates (Transcript Volume 14) had a fire in a spare bedroom where the receptacle overheated and the adjacent bed clothing and mattress caught fire. Mr. Bates had been using a window type of air-conditioning unit connected to another outlet on the same circuit as the receptacle. It was stated that a terminal screw on the receptacle was loose and hence gave rise to the overheating condition. However, after the fire, when Mr. Bates was replacing all of the receptacles on the circuit, he noticed that four other receptacles on the circuit exhibited signs of overheating. One receptacle on another circuit also showed signs of overheating.

Mrs. B. MacPherson (Transcript Volume 18) told of her experience with a split receptacle, over the kitchen counter, where sparks and flames were expelled from the receptacle blade openings.

Mrs. M. Lorenz (Transcript Volume 18) recounted her experience with a split receptacle in the kitchen, which made a sparking sound and emitted an odour and flames and sparks from the blade openings. Three different split receptacles in the kitchen failed on subsequent occasions, although not in the dramatic manner of the first receptacle.

Mrs. D. Yeo (Transcript Volume 14) and Mr. E. Pfeiffer (Transcript Volume 12) each had receptacles overheat and burn in the garage. In addition, Mrs. Yeo gave an account of the back material on a loveseat being warmed by overheating of a receptacle in the wall behind the furniture.

(xiii) Repairs. Most witnesses testified that, once a problem had been corrected, they had experienced no further trouble. Sometimes other receptacles on either the same circuit or another circuit would malfunction. Several home-owners did not perform any remedial work either when the problem occurred or since then. Others attempted to locate the source of the problem and make repairs but were not entirely successful. Some home-owners who did execute satisfactory repairs stated they had experienced difficulty in remaking connections: insufficient wire was left because either the wire broke off inside the outlet box or burned back and became brittle and unsuitable for terminating.

(xiv) Time Period. Most home-owners experienced problems in the first five years of occupation. Some experienced a continuing problem or multiple problems, but these problems were often accompanied by infrequent or technically weak maintenance and repair programmes. The home-owner who corrected initial problems and used an approved installation technique with good-quality workmanship did not experience any recurrences of the problems.

c. *Other Related Experience.* In February, 1975, the Ontario Housing Corporation — which is responsible for approximately 80,000 residential units in the province — decided to discontinue the use of aluminum in its wiring. It was testified that the ban was not a result of any risk involved but rather was an economic judgement based on the following background:

1. The Corporation had experienced problems with workmanship.
2. It made an assessment of the available literature on the experiences of aluminum wiring in the United States and the United Kingdom.
3. It compiled field information from ten projects.
4. The instructions issued by Ontario Hydro at the time caused the Corporation considerable concern.

The Ontario Ministry of Government Services conducted a study in 1974-1975 and it was decided that the use of small-gauge aluminum wire offered no economic advantage relative to copper wire and that approved connectors were not readily available throughout the province. Presumably these decisions would have restricted the Ministry from following its practice of implementing a common standard throughout the province.

The National Bureau of Standards, in Washington, D.C., prepared a report (NBSIR 76-1184) for the Tri-Services Committee on Building Materials in 1976. The report covered the use and performance of aluminum branch-circuit wiring in military buildings, and also included results of laboratory tests and suggested guidelines for the use of aluminum wiring.

The significant results of the report are outlined below:

1. From a survey of 14 bases across the United States, it was estimated that about 4,100 military dwelling units contained aluminum-wired branch circuits. Copper-clad aluminum was used in 160 of these units; another 500 units were equipped with a combination of copper-clad and ordinary aluminum wire.
2. About 50% of the bases experienced only minor problems or none at all.
3. The remaining bases reported that 5% to 35% of the dwelling units experienced problems.
4. Several bases reported plans to retrofit the existing devices with CO/ALR devices.

The above report is yet another example of the observation that aluminum-wiring problems can be localized, do occur only in some areas, and are found in projects in differing jurisdictions.

2.7.4 Maintenance and Alterations of Wiring Systems

a. Home Wiring by Handymen. With a well-educated and sophisticated public, with the high cost of hiring licensed electricians, and with the Canadian tradition of self-help, it is not surprising that many householders extend or alter the wiring systems in their homes or get friends to do the modifications for them.

The Commission encountered many instances of householders who themselves had made repairs without the assistance of a trained electrician and without the benefit of inspection by Ontario Hydro. These householders ranged from well-qualified technical people to the uninformed.

In most instances, the object was to save money and it is not surprising that cheap materials and shortcut methods, which an inspector would not approve, were used. The Commission learned that, on occasion, handymen had unknowingly introduced hazards into homes. Most handymen were reluctant to have their work inspected for fear that inspectors would not pass it and that replacement would increase the cost. There is a suspicion abroad, which may or may not be correct, that inspectors tend to favour work done by licensed electricians and to reject the work of handymen. It is easy to see how this favouritism could arise, since many handymen have more faith in their own ability than is warranted.

b. Maintenance of Wiring Systems. Wiring systems are basically maintenance-free. The normal components requiring maintenance are those associated with mechanical movement and electric contacts, such as female-blade contacts in a receptacle. Since the introduction of aluminum-wired branch circuits, however, emphasis has been placed on checking the wiring system for signs of heating. The Commission heard evidence that home-owners inspected the electric system for over-heating with various degrees of competence, ranging from no deliberate effort to a testing technique using a transistor radio.

The Research Division of Ontario Hydro conducted tests that verify, with consistency, that embossing tape may be used to identify receptacles about to overheat. The technique, which was discovered accidentally, consists of embossing a letter on an office-stationery type of embossing tape, and placing the tape on the face of the receptacle. The embossed letter will begin to fade well before the receptacle has overheated (Ontario Hydro Research Reports 75-458-K and 76-325-K). However, the tape is prone to fall off the receptacle face owing to the effects of humidity or to the drying out of the adhesive over a period of time.

Another method of detecting early-warning symptoms of imminent trouble with device termina-tions and connections is done with a battery-operated transistor radio. This method, which was described by a witness as part of his evidence, is: first, load the electric circuits by connecting a load to the last outlet on the circuit; second, tune the transistor radio to a location where there are no stations or static noise, and turn up the volume; next, test each outlet by placing the radio close to the outlet. If the radio produces a burst of static when placed near an outlet, that is a good indication of a restriction in the current flowing through the outlet terminations or connections.

Unfortunately, most home-owners are not technically knowledgeable enough to determine easily the last outlet on a general circuit. If the contractor were to provide a wiring diagram, the loca-tion of the last outlet would be known.

c. Remedial Action by Home-Owners. Several home-owners gave evidence about difficulties that they had experienced in either obtaining advice regarding some aspect of an aluminum-wired system or in trying to hire an electrician to perform repair work.

When the publicity of the news media, the Ontario Hydro safety-information card (Figure 56), the home-owners' association letters, and other sources increased their awareness, people requested information from the authorities. The authorities responded within reason to the public's request for information. Unfortunately, the authorities themselves at this time did not have a concensus of opinion regarding the satisfactory long-term solutions to the problems; as a result, the public was not always reassured by the advice given by the authorities.

In two separate locations in Ontario there was a concentration of aluminum-wired homes where problems were occurring. This situation prompted the Electrical Inspection Department of On-

tario Hydro to organize special procedures to deal with the inquiries.

In the Brampton area, the local inspection department set up, in January 1977, a telephone-information service known as the *hot line*. By December 9, 1977, a total of 1,230 calls had been received and 431 home visits, in response to the calls, had been made by inspectors. The following lists the problems reported as a result of home visits:

1. Forty-six overheated receptacles in normal use.
2. Fifty-three overheated receptacles caused by home-owner misuse, including the connecting of air conditioners, freezers, and clothes dryers to general circuits.
3. Fifteen defective twist-on connectors.
4. Thirty-seven incidents involving panelboards, such as burning of bus bars, poorly fitting fuses, and overfusing of circuits.
5. Forty-eight faulty wiring systems installed by home-owners.
6. The hot line received 22 calls from people who thought they had aluminum wiring in their homes but, in fact, had copper.
7. In 89 cases, inspectors could not locate a problem.
8. In 121 cases, the inspectors gave advice or found a variety of problems.

Thus the great majority of the calls were for information only, but about 8% concerned faults which the home-owner himself had created and about 8% were for faults over which he had had no control.

In Ottawa, where some 20,000 homes were reported to be wired with aluminum conductors, one of the electrical inspectors from Ontario Hydro's Ottawa Region was assigned the task of investigating reported problems. An analysis of the inspector's diary indicated that 101 visits were made over a period of three years. A summary of overheated and other receptacles replaced is indicated in Table 36.

Table 36

SUMMARY OF REPLACED RECEPTACLES IN OTTAWA

Condition	Number of Receptacles			
	Oct. 1974 to Dec. 1975	Jan. to Dec. 1976	Jan. to Feb. 1977	Oct. 1974 to Feb. 1977 Total
On heavily used circuits	19	0	0	19
On lightly loaded circuits	0	0	0	0
On circuits with nature of loading unidentified	52	0	0	52
Additional number of receptables changed	192	6	3	201
Total number of receptacles per time period	263	6	3	272

Home-owners experienced difficulties in finding electrical contractors or electricians to do remedial work on aluminum-wired systems mainly because:

1. The majority of electrical contractors and electricians are experienced in the use of only copper conductors for branch-circuit wiring.
2. Within the electrical industry there is no concensus of opinion regarding remedial work and tradesmen are confused as to what technique should be used to effect a safe and

reliable repair. This confusion is not confined to just the electrical industry. Equally uncertain are local building officials, technical experts, and such government agencies as the Ontario Housing Corporation.

3. The skill of electricians in tracing a faulty circuit varies considerably between individuals. Given enough time, most tradesmen are capable of finding the problem. However, time is an expensive commodity, and a contractor may decide that it could be detrimental to his business image if he undertook repairs of an installation that resulted in a high labour cost and the almost-certain irritation of the home-owner.

4. No wiring diagram is normally available to show how the wiring is installed, and this increases the time and expense needed to locate problems.

d. Interchangeability of Copper- and Aluminum-Wiring Devices. Many householders who have experienced problems with aluminum wire are confused because the new CO/ALR devices do not constitute a complete system. The system is incomplete because it is part of a technology still under development. The CO/ALR specification issued in 1975 is still provisional.

In the market place at the present time, a consumer may purchase:

1. A variety of receptacles of binding-head screw type that are suitable for copper wire only. However, not all of these devices carry any mark to indicate that they must not be used with aluminum wire.

2. Receptacles of the push-in (backwired, or quick-wire) type that are suitable for copper wire only. To deter their use with AWG-12 aluminum wire, the wiring holes are only large enough to accept AWG-14 wire, which is standard for copper.

3. CO/ALR receptacles that are suitable for both aluminum- and copper-wiring systems, but mandatory for aluminum wiring. These receptacles are usually more expensive than the above varieties.

4. A variety of pigtail connectors, none of which is suitable for connecting solid-aluminum wire to extra-flexible copper wire. These connectors are too small to be marked individually about the restrictions to their use.

A special-service connector, approved by the Canadian Standards Association and suitable for almost all applications of pigtail connectors, is not yet on the market.

Today, by far the greater demand is for copper-wire devices. Since CO/ALR devices are more expensive and are not mandatory for copper, and since the use of aluminum wire in residential wiring has declined somewhat in recent years, the Commission heard that CO/ALR receptacles are not usually available throughout the province. The likelihood that some unsuspecting home-owner may use non-CO/ALR copper receptacles for replacing receptacles wired with aluminum is a cause for concern now; it is even more likely that this possibility may occur a few years hence when the adverse publicity against aluminum wire will likely have subsided.

2.7.5 Installation and Inspection

a. Differences between Aluminum- and Copper-Wiring Installation. Contractors, technical experts familiar with electric terminations, technical-school teachers, and Ontario Hydro inspectors have indicated that aluminum wiring is less forgiving than copper, and that a consistently higher level of workmanship is essential when working with aluminum. The electrical residential-wiring industry has been accustomed to copper wire for a long period, but it lacks comparable experience with aluminum wire. When electricians have been trained to work with aluminum, or when Ontario Hydro inspectors have been exacting during their inspection of aluminum-wired homes, aluminum wiring can be made to perform satisfactorily. However, to expect such a conservative, cautious attitude among electricians, inspectors, and contractors throughout the province would perhaps be unreasonable until a vigorous campaign has educated those concerned with the need for particular care when using aluminum wire. In particular, electricians need to avoid nicking the wire, to be careful to form proper loops around binding-head screws, to tighten these screws with a torque of 12 lb-in, to use only CO/ALR and other authorized devices, and, in general, to use high-quality workmanship.

Aluminum is not as good a conductor of electricity as copper. In consequence, aluminum wires of greater diameter are used, but these are more difficult to shape accurately into loops to fit binding-head screws. This introduces another difficulty in the use of aluminum. Thus the workmanship associated with aluminum wiring is likely to be more time-consuming and expensive than the quicker style of installation of, for example, a copper-wired push-in receptacle, and hence tends, to some extent, to defeat the economic objectives that led to the use of aluminum wire in the first place.

b.   Pattern of Failures. The pattern of failure in the residential aluminum-wiring system, as reported to the Commission, is not uniform. There are large sections of Ontario and also large parts of Canada outside of Ontario that reported few, if any, failures. One such region is centred about London where the inspectors early warned electrical contractors to use particularly good workmanship with aluminum wire.

On the other hand there are some districts where many householders reported failures. Enough failures were examined by Ontario Hydro inspectors to convince the Commission of the existence of areas in which failures are relatively more numerous.

To a considerable extent more failures were reported in those rapidly developing areas where a few years ago the demand was strongest for many new residences at affordable prices. Troubles were not confined to such areas, but it would appear that builders who tried to make a profit and still provide housing at reasonable cost were more likely to attempt to save money by using aluminum wiring when it was cheap, by using cheap and sometimes unauthorized devices, and by demanding rapid, and hence a poor standard of, workmanship. The inspectors, who should have checked these undesirable practices, were overloaded by the rush of work; sometimes they were hindered in the performance of their duties; and sometimes they were not yet fully alert to the potential problems with aluminum wire and to the need for superior workmanship. Some, but not all, families moving into new homes increased the hazard, knowingly or unknowingly, by using heavy loads of appliances, by making incorrect alterations or repairs, and occasionally by overfusing.

c.   Role of the Contractor. In the Ontario residential-building industry the subtrade work, including that of electrical contractors, is highly competitive, and there is consequent pressure to reduce costs and take shortcuts. Given a choice, electrical contractors are reluctant to use aluminum wire in residential wiring systems. There has to be either a substantial cost advantage or a severe shortage of copper wire before a contractor chooses to use aluminum wire.

Normally there is no contract between the purchaser of a new home and the electrical contractor, who has contracted directly with the builder. When the electric work is finished, the electrical contractor makes a statutory declaration that he has completed his work and fulfilled his contract obligations. Normally he is required to present, as one of the contract obligations, the Inspection Certificate of Completion from the Electrical Inspection Department of Ontario Hydro. The issuance of the Inspection Certificate of Completion does not relieve the electrical contractor of his responsibility to perform his work in compliance with the Electrical Safety Code. The responsibility of the contractor to install electric equipment and wiring in a workmanlike manner is set out in the following rules of the Electrical Safety Code (Exhibit 36):

> **2-018 Defects**
> (1) Every contractor who has performed work on an electrical installation and has been notified by the inspection department that the installation does not conform to this Code shall remedy all defects in workmanship and replace all electrical equipment that is not approved within such time and in such manner as the notice from the inspection department directs.
> **2-036 General.** No contractor shall perform any work on an electrical installation in any manner contrary to the requirements of this Code.
> **2-108 Class of Workmanship.** Careful attention shall be paid to the mechanical execution of the work in connection with any electrical installation, and any installation that has been badly arranged or poorly executed either generally or in any particular will not be accepted by the inspection department.

Many contractors like to maintain that the issuance of the Inspection Certificate of Completion implies that the work has been performed in a satisfactory manner and, hence, they are relieved of their contractual responsibilities.

The current procedure of the Electrical Inspection Department for inspection of residential installations is too cursory and inadequate to check the installation work thoroughly. The contractors are responsible for testing and supervising the work to insure that the system is indeed installed correctly. From the evidence presented regarding the experience of some home-owners who discovered circuits not working when they first occupied the house, it is obvious that some contractors conduct a very superficial testing and supervision programme. The attitude apparently is that the contractor can avoid having to test or correct whatever the inspector misses.

This places on the home-owner the burden of following up and having the electrical contractor correct the defects in the installation under the home warranty. The normal period of warranty covered by a standard electrical contract is one year from a date close to the issuance of the Inspection Certificate of Completion. This can be a disadvantage to the home-owner who moves into a house that has been left unoccupied for a year or so after completion. The home-owner is still covered under the present Housing and Urban Development Association of Canada one-year warranty, but this often increases the frustration of a new home-owner in an attempt to get the builder to correct the problems under the HUDAC warranty program. The HUDAC warranty has a considerable number of unsatisfied claims registered against it.

d. *Role of the Electrical Inspection Department.* The public has an implicit faith that, when an installation has been inspected and approved by the Electrical Inspection Department of Ontario Hydro, the installation is safe and will operate in a reliable manner. This faith is due mainly to the excellent reputation of the Department. However, the current inspection procedure is inadequate for a thorough check of the level of workmanship. In any case, there is no simple method for an inspector to check the tightness of dozens of binding-head screw and pigtail connections in an average residential wiring system without interfering with the work of a contractor.

The quality of workmanship is assessed visually, because any interference with the wiring system by the inspector could be construed as tampering with the installation and responsibility for subsequent faults could be denied by the contractor on this basis. It is true that an inspector can demand that a contractor provide an electrician to manually check the torque and other features of the wiring system as part of the inspection, but such a detailed examination is time-consuming and, hence, adds to the cost of the house. Furthermore, unless a very good reason is produced, the contractor will object that this kind of inspection is not usually called for with copper wiring.

It is evident from the testimony that some inspection departments do not have adequate staff to handle the inspection duties during busy periods of construction. Also, the training of inspectors to identify fire hazards and to make reports in connection with fire incidents should be improved.

2.7.6 Circuit Design and Performance

One of the major assignments of this Commission was to investigate the effects of a change from copper- to aluminum-wired electric circuits for residential use, but that change cannot be isolated entirely from other developments. In particular, since the present system of residential wiring was introduced many decades ago, there has been a great increase in the variety, number, and power consumption of appliances. It is a tribute to the foresight and caution of those who devised the present system that generally it has met these demands safely. Other changes that possibly have affected the safety and reliability of the system have occurred in the organization of the building industry, in the training of electricians, and in the extent to which householders do their own wiring.

a. *Design of Branch Circuits.* The purpose of the Electrical Safety Code is to provide in a convenient form the essential rules that must be followed to insure the safety of life and property from electric hazards. The Code is not intended as either a design specification or an instruction manual for untrained persons.

The essential requirements of the various rules in the Electrical Safety Code applicable to the design of residential wiring systems may be summarized as follows:

(i) Service. The system must be provided with a suitable service-entrance arrangement consisting of service-entrance supply conductors, the main switch, and the branch-circuit panelboard with sufficient circuits to satisfy the minimum requirements based on the floor area of the home and the supply for electric loads installed.

(ii) Branch Circuits. Specific branch circuits, suitably rated, must be provided for electric cooking ranges, refrigerators, built-in dishwashers, and similar appliances. Split-receptacle circuits must be provided in the kitchen.

General circuits must be provided throughout the house for lighting and general receptacle use. Although general branch circuits are rated at 15 amperes, they are permitted to carry a maximum current of only 12 amperes. Since the loads that will be used on general branch circuits are not known, the Electrical Safety Code limits the number of outlets to 12 per circuit.

(iii) Location of Outlets. Specific circuit outlets are located in a position accessible to the equipment that they service. General receptacle outlets are installed in the walls of every finished room or area (other than kitchens, bathrooms, hallways, laundry rooms, powder rooms, and utility rooms or closets) so that no point along the floor line of any usable wall space is more than 6 feet horizontally from a receptacle in that area of an adjoining space. The distance is measured along the floor line of the wall spaces involved.

(iv) Electrical Protection. The branch circuits must be protected by devices to automatically open and isolate a circuit if the current therein should reach a value that would produce a dangerous temperature in the conductor or apparatus connected to the circuit. The protective device also isolates the circuit when ground fault currents flow.

(v) Mechanical Protection. Wiring devices, wiring splices, and similar types of connections must be enclosed in outlet boxes. Electric wiring that is exposed to the possibility of mechanical damage must be protected against such damage.

(vi) Demand Load. The demand load on a branch circuit is considered as the connected load, if known, or 80% of the branch-circuit overcurrent-protection device, whichever is smaller.

(vii) Voltage Drop. The voltage drop shall not exceed 3% in a feeder or branch circuit that is carrying its designed demand load. The voltage drop allowed in a general branch circuit is 3% of 120 volts, or 3.6 volts. This may also be expressed as the maximum permitted impedance for a branch circuit. With a demand load of 12 amperes and a permitted voltage drop of 3.6 volts, the circuit impedance would be 0.3 ohm.

The W.P. Dobson Research Laboratory, of Ontario Hydro, conducted a survey (Ontario Hydro Research Report 77-260-K) of household electric branch circuits to determine how the impedance values of circuits in actual houses compared with the maximum permitted value. The houses, which were located in four subdivisions in different geographical areas, ranged in age from newly occupied to 10 years old. In two subdivisions the houses were equipped with copper wiring, and in the other two subdivisions the houses were wired with aluminum. The tests were conducted in these houses by checking all receptacles in the kitchen and bedrooms and, in some instances, the laundry and living room.

With an impedance of 0.3 ohm, AWG-14 copper wire could carry a current of 12 amperes for a circuit length of 57 feet. In most houses the kitchen and panelboard are normally located within about 20 to 30 feet of each other. Hence the impedance of the kitchen receptacle branch-circuit wiring should be less than 0.2 ohm. Examination of the results presented in the report indicates that approximately 30% of a sample of 197 kitchen receptacles had circuit impedance of 0.2 ohm or less. This does not agree with the expected results. The results given in the report are the exact recorded measurements. The report used the information on a relative basis as an indicator to observe certain trends. Hence, in relation to our investigation, the values must be adjusted to allow for the following factors that influenced the actual measurements:

  1. The impedance of the source, service conductors, and panelboard.
  2. The values were not adjusted to allow for measurement errors.

If the results are re-examined and an allowance of 0.1 ohm is made for the effects on the recorded values, the results are summarized in Table 37.

Table 37

SUMMARY OF BRANCH-CIRCUIT IMPEDANCES

Area	Sample Quantity	Circuit-Outlet Impedance*	
		0.3 Ohm or Less	Greater than 0.3 Ohm
Kitchen	197	94%	6%
Laundry	73	95%	4%
Living room	59	46%	54%
Bedroom	203	44%	56%
Total	532	70%	30%

Commission's note: The data shown in this table are compiled from Ontario Hydro Research Division Report 77-260-K; the values in the original table have been adjusted by an allowance of −0.1 ohm.

The data in Table 37 indicate that the impedances of the kitchen and laundry circuits are acceptable, but over 50% of both the bedroom and living-room circuit-outlet impedance exceeds the level permissible under the 1977 issue of the Electrical Safety Code. Hence it can be expected that homes built prior to 1977 will have some branch circuits where impedance will exceed 0.3 ohm and that such circuits may be considered inadequately designed.

The impedance of the bedroom or living-room circuits could be improved to an acceptable level through an increase of the size of wire (for example, from AWG-14 to AWG-12 or -10) by interconnecting the outlets more efficiently or by reducing the number of outlets per circuit.

The impedance of a branch circuit can be easily estimated at the design stage by preparing a layout drawing and scaling the length of the wiring route from the drawing. The cost of producing such a drawing should not be significant, as the architect develops scale construction drawings and the electrical contractor could modify a print (for example, a sepia) of these drawings to show the location and circuitry of the electric system. The electric-layout drawings should benefit the contractor because the inspection department, which reviews the drawings, will be aware of any aspect in the proposed design that is not in accordance with recent or imminent Code revisions.

b. *Performance, Use, and Abuse of Wiring Systems.* When the residential branch-circuit system was first designed, the only common loads were lights and a few appliances, such as toasters. Most of the present appliances had not been invented. This is true of radio and television sets, refrigerators, power tools, kitchen cutters, grinders, and grills. Particularly significant, however, has been the development of heavily loaded and intermittently operating appliances, such as air conditioners, freezers, hair dryers, clothes washers and dryers, and dishwashers. At the inception of the system, the expected loads were only a few amperes — for which it provided ample scope — but today, with the simultaneous use of numerous appliances, parts of the system may be operating at overload conditions.

The W.P. Dobson Research Laboratory of Ontario Hydro prepared a report (Ontario Hydro Research Report 75-537-K) to give some insight into the utilization patterns of wiring systems in homes. The report is a result of field measurements of the magnitude, duration, and distribution of current in the various branch circuits in the panelboards of two homes. For reference purposes the homes are identified in the report as A and B.

Home A was occupied by a family of five, the children ranging in ages from five to twelve years. Home B was occupied by a family of four and the children were teenagers. The appliances and their respective electric loadings for the two homes are shown in Table 38.

Table 38

LIST OF APPLIANCES AND RATINGS IN TEST HOUSES

Appliance	House A	House B
Water Heater	Cascade 60 4500 W, 4500 W	Cascade 60 3000 W, 3000 W
Dryer	Electric dryer, vented outside; heater 20 A, motor rating 7 A.	Electric dryer, vented inside; heater 22 A, motor rating 7 A.
Washer	Automatic. 7 ampere motor	Automatic. 7 ampere motor
Range	Four countertop burners rated 9, 7, 7, 7 amps. Two oven elements rated 11, 11 amps	Identical to House A
Refrigerator	Standard 17 cu ft, two-door model. (Separate freezer door)	Standard 17 cu ft model. Single door
Freezer	Yes. Carried 2-7 amperes	No
Television	Colour. Hybrid type. 2 amps	Colour. Tube type. Instant on. 3 amps
Toaster	One two-slice pop-up type. 7 amps	Identical
Frying Pan	Yes. Rated 11 amps	Identical
Kettle	9 amps	9 amps
Dish Washer	No	Yes. Carried 7-13 amperes
Coffee Maker	No	Yes. Carried 3 amperes
Popcorn Maker	Yes. 10 amps	No
Snow Melting Cable	No	Yes. Exterior outlet near front door. 50 ft 700 W. Not used during tests
Electrical Tools	Various tools — sabre saw, hand drill, etc.	Hand drill
Hair Dryers	No	Two — one in each of two washrooms. 1.5 amperes each
Dehumidifier	Yes. 5 amps	No
Electric Iron	Yes. 9 amps	Yes. 9 amps

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Some of the significant observations in the report are listed below:

(i) The report results show that:

1. The laundry day represents a busy day in the household and consequent large current demand.
2. Two peaks occur in homes. A late morning-early afternoon peak represents laundry work. A second, usually heavier peak represents cooking and other general activity in the evening.
3. Automatic appliances, by the nature of their application, tend to cluster. This creates a large demand peak of 70-80 amperes, which may last as long as one hour.
4. Heating circuits run out of phase with general use circuits and the total demand in a 200 ampere service is not much higher than that in a standard, 100 ampere service.
5. Individual branch circuits can, under certain conditions, run above their 15 ampere rating.

(ii) The report commented on unusually heavy currents:

People develop living habits which can result in rather large currents in 15 ampere circuits. For

example, in house A, the maximum current of 18 amperes was found several times and, in one case, registered for more than an hour. This occurred due to the simultaneous use of the freezer, electric iron and some other appliance in the basement. Interestingly, this particular circuit had been added to the panelboard recently.

Similarly, in house B, one circuit was found running at 16 amperes on one occasion. Judging from the fact that data were accumulated over only 10 days, this may be a common occurrence in this house. Surprisingly enough, fuse blowing was not a common problem in either house. This is attributed to a heat sinking effect on the fuse in the panelboard, provided neighbouring circuits are not heavily loaded as well. However, these heavy currents may cause problems at the receptacle end of the circuit.

From that same report the Commission has drawn its conclusions:

(i) General branch circuits in the bedrooms were sparingly used; in other general branch circuits the highest-recorded-peak reading of 5 amperes was in the family room of house B.

(ii) The information presented suggests that further field work of this nature is required to develop more statistically significant information regarding electric loads in typical homes.

The Commission heard evidence that the authorities were concerned about how some homeowners, who had experienced repeated blowing of fuses, followed the practice of overfusing circuits. Circuit breakers can be reset and are less sensitive to short overloads and can be changed in rating only by physically installing another breaker of a higher amperage. In connection with this problem, Ontario Hydro presented the Commission with a report (Ontario Hydro Research Report 75-468-K) which gave the results of an investigation conducted to determine the extent of fuse blowing in Ontario homes. Approximately 100,000 dwellings were surveyed with a response of 74,633 customers in single-family dwellings and 10,232 customers in multiple-family dwelling units. The overall results have been compiled by the Commission and are shown in Table 39.

Table 39

OPERATION OF OVERCURRENT DEVICES
IN ONTARIO HOMES

Fuse replacement or breakers reset within the last year	Single Family Dwellings Note 1	Multiple Family Dwellings Note 2	Total Dwellings Note 3
0 – 1 incidents	69%	78%	70%
2 – 4 incidents	26%	18%	25%
5 or more incidents	5%	4%	5%

NOTES:
1. Expressed as a percentage of 74,633 replies
2. Expressed as a percentage of 10,232 replies
3. Expressed as a percentage of 84,865 replies
Commission's note: The data shown in this table are compiled from Ontario Hydro Research Division Report 75-468-K.

The most significant results noted by the report were that:

(1) More fuse replacing and breaker resetting occurs in single family dwellings.
(2) Fuse blowing occurs more frequently than breaker tripping.

When one remembers that a 15-ampere fuse may carry a current of 18 amperes for a period of an hour, one realizes that the fuse replacement is caused by either deliberate overloading of the circuit (for example, in excess of 18 amperes for a short time) or overloading the circuit with approximately 16 to 18 amperes for a period of an hour or so.

Inrush, or starting, currents can cause fuses to blow, particularly if time-delay fuses are not used and if the circuit is already carrying a significant steady load. Time-delay fuses were developed to permit large temporary overloads to flow in the circuit for a longer period of

time than the ordinary, or non-time-delay, type of fuse permits. They function quite similarly to the ordinary fuse for small continuous overloads and for fault currents. Table 40 compares the characteristics of time-delay and ordinary fuses.

Table 40

COMPARISON OF TIME-DELAY AND ORDINARY FUSES

Actual current amp	15-amp fuse		30-amp fuse	
	Time-delay, sec	Ordinary, sec	Time-delay, sec	Ordinary, sec
30	31	3.9		
45	10	0.8	140	22
60	5	0.3	27	4.4
75	1.5	0.2	11	1.8
90	0.5	0.1	5.4	1.0

From the table we see that a 15-ampere ordinary fuse with a 45-ampere overload current flowing would operate within 0.8 second while a 15-ampere time-delay fuse would operate after 10 seconds. This time delay before operation satisfies the nuisance of fuse blowing and yet provides adequate overcurrent protection. Table 40 also shows that if the 15-ampere ordinary fuse in the previous example is replaced with a 30-ampere fuse of the same type, the new fuse would carry 45 amperes for 22 seconds. However, since all fuses are designed to carry 110% of their current rating indefinitely, it is obvious that, if the overload current were 30 amperes instead of 45 amperes, both the 15-ampere time-delay and ordinary fuses would operate in 31 and 3.9 seconds, respectively, but the 30-ampere fuse would not blow. Thus the danger of overfusing with the 30-ampere fuse is that protection is not provided for current of less than 30 amperes.

The ability of a fuse to carry exactly 110% of its rating depends on the surrounding temperature, the inherent capabilities of the specific design to transfer heat, and the steady electric loading on the circuit prior to the onset of inrush current.

Householders generally are unaware of the branch-circuit wiring layout of their homes. They discover which fuses control which outlet only by a trial-and-error procedure. They do not know the appropriate rating of any particular circuit. They infer this information from the fuse already in place and how frequently the fuses blow.

A major step in correcting the overfusing problem is to insure that the electrical contractor fills out the panelboard-circuit-destination legend and also indicates the maximum fuse rating and type of fuse to be used in each circuit.

c. *Inrush Currents and Light Flicker.* Another problem of inrush currents during the starting period of motors is their large influence and effect on flicker in lighting systems. During their testimony, several home-owners expressed concern with flickering and dimming of lights which they perceived as the incipient stage of an expected aluminum-wiring-termination disorder. While motor-inrush currents may well be the cause, as outlined above, flickering and dimming also can be caused by fluctuations in voltage from other origins. Light flicker may be defined as the visual sensation experienced when sudden changes occur in the illumination level. Research Report 55-566 was prepared by the Research Division of Ontario Hydro as a guide to indicate whether or not the flicker in lighting systems due to sudden voltage fluctuations is likely to be perceptible or objectionable.

The salient features of the report and conclusions made by the Commission are as follows:
(i) The report defines two types of flicker, namely, cyclic and non-cyclic flicker. "Cyclic flicker is defined as that flicker which occurs in rapid or near rapid succession with fixed regularity." The source of this type of flicker normally is outside the home (for example, seam welders or

Table 41

STARTING CURRENTS WITH "AS FOUND" SOURCE IMPEDANCES FOR 120 VOLT APPLIANCES

Appliance (Name Plate Current)	Impedance (Ohms)	Normal Start			Stalled Rotor			Remarks
		Instantaneous Peak Current (A)	Duration (s)	Avg. RMS Current (A)	Instantaneous Peak Current (A)	Duration (s)	Avg. RMS Current (A)	
Air Conditioner (9.6)	0.8	46	0.70	28	43	8.1	30	
(12)	0.4	76	0.39	47	74	3.44	52	
(12)	0.4	69	0.27	43	69	6.24	49	
Washing Machine (7.0)	0.40	28	0.25	18	Not Obtained	–	–	Start of spin cycle
(9.5)	0.25	58	0.30	34	Not Obtained	–	–	loaded with wet cloth
Microwave Oven (15)	0.53	59	(Variable)	X	Not Applicable	–	–	
(15)	0.65	23	(Variable)	X	Not Applicable	–	–	
Lawn Mower (8)	1.0	51	0.80	X	Not Obtained	–	–	Blade cutting 5" grass
Vacuum Cleaner (3.6)	0.40	17	1.33	X	Not Obtained	–	–	Nozzle covered with carpet
(7.0)	0.40	50	0.45	X	Not Obtained	–	–	
Dishwasher (6.9)	0.75	50	0.15	27	Not Obtained	–	–	Water discharge pump start
Refrigerator (6.0)	0.75	28	0.50	18	32	5.0	23	
(5.2)	0.50	29	0.42	18	28	1.9	20	
(6.9)	0.30	31	1.2	20	Not Obtained	–	–	
(–)	0.40	30	0.37	20	30	3.17	21	
(–)	0.30	18	0.60	12	17	1.76	12	
Freezer (4.0)	0.55	23	0.40	15	22	1.94	16	
Drill Press (9.4)	0.75	22	0.25	11	Not Obtained	–	–	} Unloaded
Portable Drill (1.6)	0.8	6	0.6	X	Not Obtained	–	–	

NOTES:
X Non sinusoidal current waveform. RMS value not determined

spot welders) and the flicker is transmitted to the home via the electrical-utility distribution network. It also may be generated within the home by some makes of dimmer switches which use a static-control technique.

Non-cyclic flicker normally is irregular in both frequency of occurrence and duration of the sudden voltage fluctuation. Non-cyclic flicker may be caused in the home by electric motors in refrigerators, deep freezers, air-conditioning units, furnace fan motors, or oil-burner motors, where the inrush current momentarily overloads the home wiring system.

(ii) "Flicker which is just perceptible becomes more noticeable as the magnitude of the sudden change in light output increases. Ultimately, a value is reached at which the flicker just interferes with the task being performed and hence becomes objectionable."

In conjunction with its report on the influence of motor-inrush currents on flicker in lighting systems, the W.P. Dobson Research Laboratory of Ontario Hydro prepared a report (Ontario Hydro Research Report 63-212) on recommended guidelines for electrical utilities to practise. The report recommended 75 amperes as the maximum starting current. This amperage was based on the number of customers per transformer, the length of run of each customer service, the number of customers having air-conditioning units, the capacity of the transformer, the location of dwelling units having air-conditioning units relative to other services and the transformer location, and the number of starting and stopping operations per hour.

With the present widespread use of a large number of heavy-duty appliances, the basis of making the recommendation of 75 amperes may not be realistic. The inrush currents for various heavy-duty appliances are shown in Tables 41 and 42.

Table 42

STARTING CURRENTS FOR 230 VOLT APPLIANCES

Appliance (Name Place Current)	Impedance	Start			Stalled Rotor		
		Instantaneous Peak Current (A)	Duration (s)	Avg. RMS Current (A)	Instantaneous Peak Current (A)	Duration (s)	Avg. RMS Current (A)
Air Conditioner (13.5)	0.21	75	0.52	47	76	3.38	54
(22)	0.18	150	0.48	93	141	–	92
Clothes Dryer (24)	0.13	57	0.55	30	Not Applicable		–

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In Table 42 it can be seen that the starting current of today's typical 230-volt air-conditioning unit equals or exceeds the 75-ampere guideline. Perhaps more alarming is the availability of 120-volt-rated appliances which have instantaneous-peak starting currents of between 50 to 75 amperes and an average root-mean-square current of 27 to 47 amperes.

Several witnesses testified that a higher-than-expected number of their incandescent lamps had burned out. Some witnesses stated they had had the same experience even with lamps from different manufacturers and in a different price range.

The causes of lamp flicker may not be related directly to differences in performance between aluminum- and copper-wired systems. However, home-owners may become unnecessarily alarmed or anxious when the lamp flicker reaches too high a level. It would appear prudent, therefore, that consideration should be given to a review of voltage fluctuations in a residence, the maximum inrush current permissible for appliances, and reliability testing of incandescent lamps for burning life within these voltage-fluctuation parameters.

2.7.7 Distribution and Recall of Electric Equipment

Electrical contractors normally purchase their electric equipment through electrical distributors. Householders normally purchase items of electric equipment from hardware stores or other stores that specialize in providing supplies for home handymen.

Most branch-circuit wiring components are too small to be imprinted with information about their use and installation. This information normally is printed on the wrapper or on a carton when several units are packaged together. The Commission heard evidence that related to the practice followed by some stores of selling individual devices unpackaged in an open bin without any display of either application information or installation instructions. This is particularly serious when a product, which may have been approved for restricted use, may appear to the uninformed to be the item he requires.

The introduction of CO/ALR devices has caused confusion regarding their availability as a complete system and their interchangeability with non-CO/ALR devices. In any case, some homeowners living in homes wired with pre-CO/ALR devices may not know that they must use special devices for aluminum wiring. It may well be that, in regions within Ontario where CO/ALR devices are not yet available, many handymen are unaware of the existence of the two grades of devices. Through ignorance or in attempts to save money, handymen may be tempted to buy non-CO/ALR devices — legal for use with copper wire — which are for sale in retail stores, and then use these devices with aluminum wire, for which they are not authorized.

Since the sale of electric devices is not restricted to qualified electricians, and this situation is not likely to change, Ontario Hydro, in conjunction with members of the electrical industry, should develop a program to disseminate information to the public regarding the safe use of wiring devices.

The Canadian Standards Association has indicated that it may be possible in the future to use symbols to identify the type of wire to which the particular device may be connected. Caution would have to be exercised to not increase confusion in the field, since time would be required to sell those devices, already on the market, which are not yet so identified.

The Commission heard extensive discussion during testimony regarding product-recall procedures. The discussion centred around:

(i) Equipment for Sale. It is unfortunate that Ontario Hydro has no statutory power to order the removal of defective or uncertified equipment from distributors' shelves. The only legal recourse open to Ontario Hydro is to obtain a summary conviction against the party offering such equipment for sale.

However, Canadian Standards Association can insist legally that manufacturers recall products that are not certified but that bear the Canadian Standards Association mark or for which the certification has been cancelled. Products that have been certified by the Canadian Standards Association can have their certification cancelled if field experience shows the products to be hazardous, if the manufacturer has failed to comply with a standard revision, if the manufacturer's quality assurance becomes unacceptable to the Canadian Standards Association, or if there is failure to comply with the terms of the Service Agreement.

(ii) Equipment in Homes. For the equipment already installed in homes, the situation is more complicated and may be divided into two categories:

1. The equipment when installed was approved for the application but subsequently has been judged to constitute a hazard in a manner not anticipated when certification was granted.
2. The equipment was never certified for the application for which it was installed.

Here again, Ontario Hydro has no statutory power to order the removal of installed defective or uncertified equipment. The only legal recourse for Ontario Hydro is to obtain a summary conviction against the party who committed the offence of failing to comply with the Electrical Safety Code regulations. However, under summary conviction the charge must be laid within six months of the incident.

For equipment that was certified at the time of installation, the only reasonable corrective action that Ontario Hydro can take is to inform the public and to offer advice on how modifications or repairs can be effected. If uncertified equipment was installed, Ontario Hydro should be granted legal powers to order corrective measures and to enforce their execution.

2.8 Evaluation of Available Statistical Data

This section is concerned with an examination of previous surveys on the reliability and safety of residential branch-circuit wiring, and with the analysis and interpretation of existing statistical data. Information of this nature is limited and Section 2.17 of this report contains recommendations that improvements be made in the collection of data.

One source of data considered for statistical analysis is the hot-line calls made to Ontario Hydro, and a second source is the United States Consumer Product Safety Commission. Some of these data were submitted as evidence and used by one witness or another to support claims. The validity of these claims may be assessed by judgement but, in the Commission's view, the data should be regarded as collections of anecdotes. Structured statistical tests should not be applied to them without more control over the design, the collection, and the selection of the data. It would be misleading to analyse the data statistically and thereby convey the impression that it is possible to make strong inferences from them about the relative safety and reliability of aluminum versus copper.

Another source of data is the internal reports of the Canadian Standards Association. These indicate that in the period from 1973 to 1977, the Association received reports of 284 failures in receptacles and devices wired with aluminum and of 50 failures with copper in the same period. Unfortunately, there is no information about whether this sampling was biased but, in view of the fact that only approximately 10% of the residential units in Ontario are wired with aluminum, the figures suggest strongly that aluminum wiring is less reliable than copper wiring.

In R.L. Hicks' report, entitled *Residential Wiring Research Program, Detailed Results* (Exhibit 44A), one of the conclusions (page 29) is that "the CO/ALR receptacle will increase the life of connections in aluminum-wired household receptacle circuits by at least 100 times." The Commission has found no documentation to substantiate such a broad claim. Page 12 of the same report records a limited survey of 26 instances of failure. Of these, 10 involved problems with aluminum-wired systems and eight with copper. The statement is followed by "thus the number of problems reported with aluminum wired systems was roughly the same for copper wired systems," which takes no account of the fact that only about 10% of the residential units in Ontario are wired with aluminum. When this fact *is* taken into account, the probability of at least 10 aluminum-wired homes showing up in a random sample of 26 is about one in ten thousand, a very unlikely event.

J.A. Dicker, on page 4 of his report, entitled *Public Electrical Safety in Ontario* (Exhibit 34), comes to a conclusion similar to that of R.L. Hicks. The Commission agrees that the absolute level of risk for either aluminum or copper appears to be low, but has little doubt that the figures quoted by R.L. Hicks and J.A. Dicker do indicate that, relatively, a difference does exist.

These pieces of evidence, for what they are worth, and the results of a survey conducted in the United States — which is described in the following section — all suggest that aluminum wiring is less reliable than copper wiring in residences. The Canadian data included residences in which it is now known that the workmanship was poor and unauthorized devices had been installed. The United States survey certainly included residences with devices never approved in Ontario. Thus the premise that aluminum is considerably less reliable than copper may apply to a circumstance that, in Ontario, has been largely rectified, as is discussed in Sections 1.8 and 2.2.

To the Commission's knowledge, the only important source of up-to-date statistical data for Ontario is the report of the Fire Marshal, entitled *1976 Fire Losses in Ontario* (Exhibit 198). Henceforth this will be an annual report, which shows promise of being a rich source of comparative data of fires that occur in buildings in which aluminum wiring is used for the electric branch wiring. Because 1976 was the first year in which reports of fire incidents were organized in this way and in such detail, some classification errors crept in which have now been resolved. Table 43 shows a corrected summary. These figures suggest that there is no strong evidence that aluminum is more dangerous than copper at the fire level-of-risk. Unfortunately, the force of the

comparison is weakened somewhat by the known difficulty in determining the source of ignition — 6,000 incidents out of 23,000 were unclassified — and the comparison is clouded by the known heterogeneity of standards and procedures applied by the multitude of fire chiefs throughout the province. The table makes clear that electric wiring is only a minor source of fire-related incidents in Ontario.

Table 43

1976 FIRE LOSSES IN ONTARIO

Source of Ignition	Incidents Classified as due to Electric Wiring		Incidents Classified as due to causes Other than Electric Wiring	Total
	Aluminum Wiring Present	Copper Wiring Present		
Identified	62[1]	1,061[2]	15,086	16,209
Unidentified	20[3]	852[4]	–	872
Unclassified or unknown	–		6,028[5]	6,028
Subtotal	82	1,913	–	–
Total	1,995		21,114	23,109[6]

Commission's notes: 1. Includes incidents classified S1001–S1008. 2. Includes incidents classifed S1040–S1048. 3. Includes incidents classifed S1009. 4. Includes incidents classified S1049. 5. Includes incidents classified S1099 and S1000. 6. Total includes all incidents (from Provincial Totals, p. 1). 7. The data in this table are compiled from the Fire Marshal's 1976 report (and later revisions) on fire losses in Ontario.

2.9   Consideration of Surveys to Collect Data

Very early in this Inquiry on Aluminum Wiring, it was recognized that adequate, reliable statistical data on the relative field performance of pre-CO/ALR devices wired with copper or aluminum did not exist in Ontario. The Commission considered whether or not to conduct a survey to collect information on this subject.

It was thought that the survey, if it was to be useful, should be conducted in two phases. Phase I would entail interviewing the occupants of homes in a large random sample, at a relatively small cost per home, to determine the type of wiring. This would be necessary because it is impossible to obtain reliable statistics of the relative utilization of copper and aluminum, the two materials in residential circuits, by year or by geographical location. In the past there has been no reason to identify the type of wiring in a residential unit and no such records were kept by any agency. It is probably true to say that many, perhaps a majority, of Ontario householders are not aware of the type of wiring in their homes. The results of Phase I could be used as a frame for, in Phase II, a random selection of a smaller sample of perhaps 200 aluminum-wired and 200 copper-wired units for thorough examination of the details of their wiring systems and the history of any problems encountered with the systems.

However, for the following reasons, it was decided not to conduct a field survey in Ontario of the reliability of pre-CO/ALR devices wired with aluminum or copper:

1. Existing laboratory data on pre-CO/ALR devices indicated that some connections with aluminum wire were less reliable than with copper. These tests identified steel binding-head screws, push-in connections, and zinc plating of current-carrying parts as factors contributing to unreliable operation. The regulatory agencies had already taken corrective action to prohibit the use of these items in residential wiring devices intended for use with aluminum. CO/ALR receptacles became mandatory in 1976 for use with aluminum wire in residential wiring. It is interesting to note that the flurry of regulatory action, taken by Ontario Hydro and the Canadian Standards Association from 1975 to 1977 with respect to aluminum wiring, was not considered necessary with respect to copper wiring (see Sections 2.2 and 2.6).

2. The United States Consumer Product Safety Commission initiated a pilot survey in the United States, similar to that considered for Ontario, at a cost of about one million dollars. The Commission of Inquiry on Aluminum Wiring recognizes the differences between Canadian and United States practices and devices, but there are considerable overall similarities. The results of the United States survey are now available and confirm that pre-CO/ALR devices with steel binding-head screws wired with aluminum are less reliable than those wired with copper in both 15-ampere and 20-ampere circuits.

3. A survey in Ontario, similar to that referred to in 2., would have considerably delayed the conclusion of this Commission's inquiry and would have cost the taxpayers of Ontario substantial sums of money.

In considering the United States surveys, this Commission has prepared the following summary of and comments on the *Pilot Survey of Branch Wiring Systems in Montgomery County, Maryland,* a report of the United States Consumer Product Safety Commission, dated September 1977. This report, which is included in the pleadings file for CPSC v. The Anaconda Co. et al., has been discussed in Section 2.6.4.

The study was intended merely to guide a contractor in the future to efficiently design and implement a more extensive survey in four additional areas, representing diverse geographical and temperature characteristics, in the United States. (It is understood that a contract for such a survey has been given to the Franklin Institute, of Philadelphia, Pennsylvania.) However, the results of the pilot survey, small as the sample size was, provided substantive material to support

the hypothesis that the relative risk of overheated duplex receptacles in aluminum-wired circuits was significantly higher than in copper-wired circuits.

Adequate care appears to have been taken to conduct a survey with a high degree of precision and a minimum of potential bias. The senior author of the report was a statistician; Dr. Leslie Kish, a well-known statistician and author in the survey-sampling field, was the consultant on the study design and the implementation plan. Careful examination of the built-in statistical precision and the possible sources of bias reveals few vulnerable points. A differential-refusal rate for aluminum-wired homes and copper-wired homes could result in a hidden bias: aluminum homes with problems may be less likely to refuse to co-operate than copper homes with problems, but the above report shows a refusal rate too small to result in a reversal of the comparisons observed.

In spite of the small sample size, the comparisons are impressive and convincing because of their consistency. In 39 aluminum-wired homes, 16 of them (41%) had at least one circuit that overheated to 75°C.; in 57 copper-wired homes, only one circuit (2%) overheated. Failure-rate comparisons similar to the above are consistent throughout the study regardless of whether they were made on a home basis, a circuit basis, or a receptacle basis.

2.10   Recommended Action in Respect of Existing Residential Wiring

Discussion

Sections 1.8 and 2.7 discussed the question of the safety and reliability, for residential use, of aluminum-wired electric circuits in comparison with copper-wired circuits.

Between 1948 and 1965, aluminum wiring was installed in only a few houses. There is a lack of firm statistical data but a sufficiency of evidence and opinion to suggest that these installations have remained safe and reliable. The limited tests carried out during this period support the same conclusion. From 1965 to 1974, a great demand for housing coincided with a shortage of copper. Because it was cheap and abundant, aluminum was substituted for copper. The demand meant that the substitution of aluminum in a system designed for copper was begun hastily, and also that, in some cases, the workmanship was not as good as it should have been. Problems soon arose and, as the number of houses rose, so did the incidents until about 1976. Throughout the period from 1965 to 1976, it seems clear that aluminum wiring was less reliable than copper.

During the same period, Canadian and United States authorities monitored the situation and began tests. Rectification depended upon understanding the complex reasons for failures. It took some time to discover that the principal cause of failures was loose connections, resulting from poor workmanship, which could not be seen by visual inspection. Among other causes contributing to failures with aluminum wiring were steel screws, zinc-plated screws, receptacles of the push-in type, and poor looping of wire at the termination. Some of these factors had never been authorized in Ontario, others came to be prohibited as their nature became apparent, while at the same time the introduction of more stringent specification tests led to improved devices.

Sections 1.8 and 2.2 presented evidence that the problems diminished once the public, the authorities, and the electrical industry had been alerted and had taken action. This was strikingly illustrated in Ottawa where in the last three months of 1974 and all of 1975, Ontario Hydro inspectors were called upon to replace 263 faulty receptacles — including seventy-one which had overheated — but in all of 1976, only six, of which none had overheated. (See Table 36, Section 2.7.4.)

In August 1978, misinterpretation of the results, not of any real incident or fire, but of a test, led to widespread publicity. In response, the office of the Commission received only one call from a householder, and Ontario Hydro inspection offices in Ontario (including the hot line in Brampton) reported that in the following two weeks they had received thirty-seven calls — of which most were for information — and inspectors had visited seventeen homes. During their visits the inspectors found six overheated receptacles and one defect in a panelboard on a copper-wired circuit which was caused by an electrician's faulty work. (The preceding information is a revision of earlier data, received by telephone, which were quoted in Section 1.8. The written confirmation was received too late to be included in Part 1 of this Report.) These findings suggest that the improvement, as detailed in the earlier evidence, is continuing and that there is not now undue cause for widespread apprehension about aluminum wiring. It appears that there are good grounds for believing that, since 1976, the reliability of aluminum-wired circuits has been markedly improved by the correction of inadequate workmanship and the replacement of unapproved devices. Nevertheless, the situation calls for continued vigilance, not for complacency.

With regard to the relative safety of aluminum wiring, one would suppose that safety would follow reliability but the evidence for such a presumption is not clear. Several witnesses stated that, in their view, aluminum was not as safe as copper, but neither they nor anyone else produced definite statistics or evidence other than opinion to support this view. As discussed in 2.8, in 1976 the Ontario Fire Marshal started for the first time to keep records bearing on the relative safety of copper and aluminum systems. The figures for 1976 suggest that, at the fire level-of-risk, there is no strong evidence that aluminum is more dangerous than copper. Unfortunately, the comparison is weakened because the source of ignition was not determined in a quarter of the

cases and different regions followed different standards for recording fire incidents.

It should be realized that it is more difficult to obtain evidence of safety than of reliability. After a minor problem, a blackened cover plate, or the like, may remain to show lack of reliability, but lack of safety is more likely to be associated with a major fire in which all the evidence may have been destroyed.

Significant in the matter of safety were the letters that the Commission received from insurance companies and adjusters, of whom only a few have issued warnings. The Commission found no evidence that any insurance rates had been raised on account of aluminum wiring.

Other important considerations connected with safety are that, of all fires, few are due to electric causes and that, of the small proportion of those few, a very small number are due to failure of residential wiring. Thus the whole question of aluminum versus copper wiring affects only a small fraction of the total number of fires in Ontario homes.

a.   Conclusion. In Canada the electrical industry estimates that about 450,000 residential units are wired with aluminum. Relatively few householders have reported problems and in most cases the causes of trouble have been associated with the use of unapproved devices, overloading, and a failure to recognize that aluminum wiring requires a higher level of workmanship than copper wiring. Most of the reported problems have been corrected and any hazard that existed has now been greatly reduced.

The replacement of all aluminum wiring with copper wiring in residences would be an enormous expense and would remove only one relatively minor source of household fires. If real concern is felt about danger from fires in homes, there are more effective ways to spend large sums to improve safety.

Recommendation 1

Only a small proportion of all fires in Ontario houses can be attributed in any way to failures in residential wiring, and effective action has already been taken to correct reported cases of poor workmanship and of the use of improper devices. It is recommended, therefore, that there is no need to undertake the vast expense that would be required to replace all existing residential branch-circuit aluminum wiring with copper.

b.   Conclusion. Any wiring, whether copper or aluminum, introduces a certain element of risk. In particular, some weaknesses in aluminum circuits, owing to poor practices, may still be present either undetected or uncorrected.

Some householders do not know the type of wire — that is, copper or aluminum — in their homes and few understand the wiring system well. Failures may occur in any system and some householders abuse their electric system. Fortunately, before wiring systems malfunction and create a major safety hazard, advance warning symptoms usually appear. Timely recognition of these danger signals would do much to reduce hazards.

The Canadian Standards Association has issued a booklet on this subject to consumers, and lists of these symptoms have been published and given limited circulation by Ontario Hydro and the Brampton home-owners' association. An extension of these efforts by Ontario Hydro and local utilities to reach all householders would lead to a reduction in hazards and would have the advantages of not only doing so for dangers due to aluminum wiring, but also of tending to reduce the many more numerous hazards from other causes.

Recommendation 2

Ontario Hydro and local utilities should inform all householders on how to recognize symptoms that warn that an electric system may be about to fail. These warning signals should be publicized widely, and Ontario Hydro should consider using television and other media for this purpose.

c.   Conclusion. Publicity would raise questions in people's minds and Ontario Hydro should take steps to answer these questions. The free inspections by Ontario Hydro have served a useful purpose, and so has the toll-free line in the Brampton area. Extension of the hot line to cover the whole province would be beneficial by insuring that all offices and inspectors of Ontario Hydro give identical advice and take the same actions. In the past, different authorities have given con-

flicting advice, thereby causing confusion.

Publicity also would alarm some people without cause; the hot line could be useful in calming unwarranted concern.

Recommendation 3

Ontario Hydro should extend its hot-line service in the Brampton area into a toll-free, province-wide telephone service to provide uniform information on all residential wiring. The existence of this advisory service and the toll-free telephone number should be given extensive publicity.

Recommendation 4

An Ontario Hydro inspector should make, without charge, one inspection of the wiring in residences of those householders who are in touch with Ontario Hydro or their local utilities directly or by referral from the hot line and who describe what seems to be a genuine problem or cause for concern.

d.   Conclusion. If Recommendations 3 and 4 are put into effect, the information service should give warnings of hazards so that the causes may be corrected. It must be realized that a few failures are bound to occur with both copper and aluminum wiring. Receptacles wear out and it is common practice to replace them. Fortunately a much smaller number of failures at terminations are occurring now as the result of corrective measures. The example of vigorous action by the inspectors in the Ottawa area shows how successful this can be. Nevertheless, some pockets of unapproved devices may remain; a few witnesses and also letters to the Commission complained of problems with unapproved devices, especially receptacles of the push-in type, still in their homes. Published reports show that devices of the push-in type tend to fail sooner than those with binding-head screws with copper or with aluminum. Devices that show any evidence of weakness should be changed, and any poor workmanship should be corrected.

It is a matter of concern to the Commission that evidence showed that some householders knew that their houses contained unapproved devices, which they had not had replaced, or poorly installed equipment on which handymen had attempted repairs without inspection, and yet they complained that their houses were unsafe. This Commission has no authority to determine responsibility for past errors, but it does consider that those who live in residences and who suspect or know of trouble should follow the advice printed and circulated by the Brampton home-owners' group — which is reproduced in Section 2.7.2 — and get the help of an inspector or an electrician. If they feel some party other than themselves should be made responsible, they can follow the same group's advice and maintain a record of the problem and the repairs.

Recommendation 5

Those householders who suspect or know of weaknesses or failures in their wiring systems should follow the advice of the Brampton home-owners' group to seek professional advice and have repairs made as necessary.

Recommendation 6

There may be localities where a quantity of unapproved materials or devices were installed with aluminum-wired systems and some of these may not have been replaced, or where there have been instances of bad workmanship with aluminum-wired systems and these may not have been rectified. If Ontario Hydro or local utilities know of or discover any such localities, they should insure that all householders in those areas are advised to arrange for an inspection of their electric systems — if that has not been done already — to make sure that no potential hazards remain undetected.

e.   Conclusion. Some householders have complained about difficulties that they have had in finding contractors willing to work with aluminum wiring. From the evidence, it appears that not all electrical contractors are adequately trained or have had enough experience to enable them to work with aluminum wiring.

Recommendation 7

Ontario Hydro, in full consultation with the Electrical Contractors Association of Ontario,

should establish and maintain in each region a list of electrical contractors who are willing and qualified to work upon and to repair residential aluminum-wiring systems. Ontario Hydro and local utilities should refer the public to these lists when inquiries are received about repairs or alterations to residential aluminum-wiring systems or when inspectors recommend that work be done. These contractors should be prepared to give free estimates of costs of proposed work.

f.   Conclusion. The Commission heard evidence of numerous failures in panelboards, and Ontario Hydro made available to the Commission several technical reports dealing with panelboard failures. From this information it appears that certain designs of panelboards have proved to be unreliable in the field.

Recommendation 8

Ontario Hydro and the Canadian Standards Association should continue to investigate panelboards and the failures reported in them and to inform inspectors, the public, and the manufacturers of any corrective action considered necessary.

2.11 Recommended Action in Respect of Wiring Systems of New Residential Units

Discussion

The distribution of electric power through residential branch circuits is an example of a developing technology. Other examples which are closely related to residential wiring are electric-transmission and -distribution systems and aircraft wiring; all initially used copper and all, after experiencing difficulties, successfully effected the change to aluminum and in so doing saved consumers much money. There is evidence and there are reports indicating that a parallel change can be made for residential systems by further development; indeed, a number of improvements have recently been accepted or are proposed.

Not only are changes being made in residential wiring systems, but also the loads placed upon them in the average home are becoming ever greater. The use of heavy-duty appliances, such as air conditioners, hair dryers, dishwashers, and freezers in Ontario households, is increasing continually. Many of these appliances take a high surge current on starting and, in some (e.g., refrigerators, freezers, and air conditioners), these high surge currents are cyclic in nature. The Ontario Electrical Safety Code now requires that such appliances be served by a separate circuit that includes no other receptacle outlets. However, in many cases a householder has no way of determining whether or not a certain receptacle — in his bedroom, for example — is on a separate circuit, and hazardous mistakes are made.

a. Conclusion. To impose a total ban upon the future use of aluminum wiring in residences would create worry in the minds of the large majority of householders in aluminum-wired houses who have had no trouble, and it would lower considerably the market value of their houses. Such a ban seems unnecessary in the light of the evidence presented. To prohibit aluminum now, when the problems with its use are recognized and are being overcome, would halt developments that may lead to cheaper and more reliable wiring systems in the future.

Recommendation 9
Aluminum wiring should continue to be authorized for use in residential branch-circuit wiring of homes built in the future in Ontario.

b. Conclusion. A new and improved grade of aluminum alloy, called aluminum-alloy conductor material (ACM), has been introduced into Ontario. Authorities agree that for residential use it is superior to the grade used previously. Its use is now mandatory in the United States.

Recommendation 10
The Canadian Standards Association and Ontario Hydro should authorize only aluminum-alloy conductor material or its equivalent, instead of EC-grade aluminum, for use in residential branch-circuit wiring in Ontario.

c. Conclusion. Evidence indicates that devices of CO/ALR and other improved specifications are more reliable than many pre-CO/ALR devices, but the present CO/ALR test specification for receptacles and switches is provisional, as is that for the special-service connector. Final specifications have not been issued for these devices and not all devices are yet available. Thus the CO/ALR devices do not constitute a complete system. Reports suggest that, although indium was introduced as an improvement for plating some devices, tin may be better and should perhaps replace indium. Other reports suggest that spring washers beneath binding-head screws improve connections and their use should be considered.

Recommendation 11
The Canadian Standards Association should review the provisional specifications of CO/ALR

devices and develop comprehensive specifications for all devices used in a complete system of residential branch-circuit wiring. Ontario Hydro should insure that devices complying with such specifications are available in Ontario.

d.   Conclusion. A simple wiring diagram would alleviate some problems and probably would not add significantly to the cost of a house. A wiring diagram would also be useful if a house is being inspected when the existing wiring installation is being augmented, or when the house is being sold.

Recommendation 12

Ontario Hydro should require all builders of new dwelling units to supply the purchaser of a unit with a wiring diagram of the unit's branch circuits, the location of the various outlets, and their connections to the panelboard. The diagram should also include the authorized rating of each fuse or circuit breaker, the type of fuse recommended (whether ordinary or time-delay), the type of wiring (whether aluminum or copper), the name of the electrical contractor, the name of the Ontario Hydro inspector, and the date of the final inspection.

2.12 Recommended Action to Develop a Future Residential Wiring System

Discussion

In any developing technology, when standards are set, they are designed to cope with the existing situation and such future developments as can be foreseen. Ultimately progress overtakes the old standards and a complete re-appraisal becomes necessary. One example occurred at the turn of the century when the present system of residential branch-circuit wiring replaced the knob-and-tube system. Similarly, in Britain during the 1950's, the residential wiring system underwent a radical re-appraisal and redesign. Several other countries have adopted the current British practice of separating the lightly loaded lighting circuits from those supplying heavy-duty appliances. For example, in Ontario, some heavy-duty appliances, such as cooking stoves and laundry dryers, must be supplied by independent 230-volt circuits. The Commission heard that householders very often augment their wiring system so that they can make use of bigger and more powerful appliances.

Even in the areas in a home previously considered lightly loaded (e.g., bedrooms, bathrooms), there is an increasing use of such powerful electric appliances as heavy-duty hair dryers and room air conditioners. The power demand from domestic appliances is likely to keep on increasing.

Limited field studies done by Ontario Hydro indicate that, during certain peak-demand periods of the day, certain circuits in a home are almost fully loaded for considerable lengths of time. Split receptacles in kitchen areas were introduced as a convenience to cope with this growing use of electricity in North American homes. Evidence and reports suggest that the removal of break-off tabs weakens the system mechanically but that, when not removed, the tabs may overheat or fail, especially if a short circuit occurs. Although problems with aluminum wiring have drawn attention to the matter, there is a need to improve the system if copper alone is considered. Overloading affects copper wiring too, and the Commission heard evidence of failures and fires in homes wired with copper as well as those wired with aluminum.

The indications are that conditions will arise for which piecemeal and ad hoc solutions will no longer be adequate. If these conditions are allowed to persist unchecked, the frequency of failures in residential copper- and aluminum-wiring systems in Ontario is likely to increase as loads become greater.

a. Conclusion. The loads placed upon residential wiring systems have risen far beyond the use that was envisaged when the present system was devised, and the number of high-power electric appliances is likely to continue to increase.

Recommendation 13

As soon as possible, Ontario Hydro and the Canadian Standards Association should organize, in the light of present and predicted loads, a complete re-appraisal of existing residential electric systems wired with either copper or aluminum. Such a re-appraisal should include conductors, devices, equipment, and installation practices.

Discussion

Owing to the danger inherent in the use of electricity in a home, the regulatory powers in matters of electric devices and equipment certification and installation practices have been primarily exercised to insure public safety. Reliability and satisfactory operation over an expected life have not been of paramount concern to Ontario Hydro and the Canadian Standards Association.

The building industry is now organized in such a way that competition drives downwards the quality of devices, equipment, and workmanship to the lowest permissible level. Since this is predicated on safety alone, reliability and durability of residential wiring become casualties. The

symptoms of this state of affairs have become evident in the case of aluminum wiring because it is more susceptible to poor workmanship. Unreliable operation of a device leading to severe overheating is a safety concern since there is the possibility that it may fail in an unsafe manner and not be contained, causing damage.

a.   Conclusion. While it is proper that the safety of residential wiring systems should have been the prime concern of Ontario Hydro and the Canadian Standards Association, reliability is also an important factor and should be taken into greater account.

Recommendation 14
    Ontario Hydro and the Canadian Standards Association should give greater emphasis to the reliability of residential wiring systems, in addition to their safety, when setting standards and codes of practice.

b.   Conclusion. Because reliability has not been considered to any great extent, there is a lack of methods for evaluating this aspect of present systems.

Recommendation 15
    It is recommended that laboratory tests and evaluation procedures for establishing the reliability of wiring devices, equipment, and systems should be developed by Ontario Hydro and the Canadian Standards Association as soon as possible. Due account should be taken of field experience in Ontario dwelling units.

Discussion
    At the present time, most copper and all aluminum are obtained by processing high-grade ores; this situation, however, is likely to change soon. Aluminum is one of the commonest elements in nature and high-grade ores will always be available. Copper, on the other hand, is a relatively scarce metal, of which known rich deposits are being exhausted more rapidly than new ones have been discovered. At the present time, the prices of the two metals are not greatly different but in the future the price of copper is likely to rise more quickly than that of aluminum. Since there is a natural desire to keep the price of housing as low as possible, the difference in the price increase is a factor that should be taken into account in planning residential wiring for the future.
    The energy requirement for extracting and refining aluminum is greater than that for obtaining copper from high-grade ores. With the depletion of these ores and the consequent necessity to obtain copper from low-grade ores, the differential in energy levels to extract the two metals will not be as significant.
    Bell Laboratories, in the United States, told the Commission that they had investigated the problem and arrived at this conclusion. In consequence, the Laboratories had developed a complete telephone system based upon aluminum wiring in case copper should become expensive or unobtainable. Their system is for low voltages and cannot be directly used in residential circuits, but the example shows that the future use of aluminum should be so considered.
    Long ago the electrical-utility industry developed satisfactory methods for the almost exclusive use of aluminum in high-current transmission lines and in modern distribution systems.

a.   Conclusion. The home-wiring industry in Canada should follow the direction taken by those responsible for distribution and transmission cables and by the Bell Laboratories, which has designed alternative systems based upon aluminum wire. Some of the troubles with the present system arose because, although it had been designed for copper conductors, aluminum ones were substituted without enough consideration of the consequences.

Recommendation 16
    Ontario Hydro and the Canadian Standards Association should consider developing a new system for residential branch-circuit wiring. The use of aluminum conductors should be considered and attention given to determining whether copper and aluminum could be made interchangeable in the system and, if so, under what conditions. The system should be designed for reliability as well as for safety with the heavier loads now in use.

Discussion

Several witnesses raised the question of the adoption of a system of crimped, or compression, connections for residential aluminum wiring. Such connections are used extensively for aluminum conductors in heavy-current, high-voltage power circuits. As mentioned above, Bell Laboratories has developed a system of crimped aluminum connections for communication circuits in case it should be decided to switch to aluminum from copper. Such connections are reliable and normally operate at a temperature close to that of the conductors to which they are connected.

The Commission heard of serious reservations about the suitability of currently available crimping lugs and tools for residential wiring. The systems of connection available at present and adequate to do a proper job require special tools, each of which is very expensive compared to screwdrivers or pliers. Electricians would have to become familiar with this type of wiring termination and might object to using the heavy special tools. No doubt the tools could be simplified and lightened. It is doubtful if an average home handyman would use such a system; he might often resort to makeshift techniques which are available but which would not make sound connections.

In the United States, the Consumer Product Safety Commission has financed experiments with crimped-connection systems. The results show that, given proper equipment and training, crimped connections can be applied successfully to residential wiring.

a. Conclusion. Given time and support, a system of crimped connections suitable for residential branch-circuit wiring could be developed.

Recommendation 17

The Canadian Standards Association, Ontario Hydro, representatives of the electrical manufacturing and contracting industries, and others concerned should undertake, through existing committees, the necessary steps to consider modifications to currently available crimped connections. Their overall suitability and acceptability for residential circuits should be evaluated, in an endeavour to develop a system of crimped connections which might form a part of a new system of residential aluminum wiring. Preferably the system should be readily adaptable to either copper or aluminum conductors.

b. Conclusion. The development and testing of any new system of wiring will require considerable laboratory and field work and will be expensive. Any new system, to be successful, must have the full support of, and be well understood by, the whole industry.

Canadian Standards Association has the main responsibility for setting electrical standards in Canada. The evidence before the Commission indicated that in the various standard-setting committees of the Canadian Standards Association, there is insufficient technical input that is independent of the electrical-manufacturing or electrical-contracting industries. This situation could perhaps be rectified by encouraging the members of the wider Canadian technical and scientific community to participate to a greater extent in the standard-setting process.

Funding is also inadequate for the task of a major re-appraisal of residential wiring.

Recommendation 18

The Electrical and Electronic Manufacturers Association of Canada, Canadian Electrical Association, and Electrical Contractors Association of Ontario should financially assist the Standards Division of Canadian Standards Association to:

1. Carry out or commission independent investigations and appraisals of residential wiring systems, particularly when major or significant technological changes are imminent in the components comprising the system or in the installation practices.
2. Carry out or commission exploratory research to supplement the data, provided by the manufacturers, in support of proposed or existing standards.
3. Facilitate greater participation by representatives of consumers and by the members of the scientific and technical community, particularly those not directly associated with the manufacturing or contracting industry, in the preparation of standards dealing with the reliability and safety in residential wiring systems.

2.13 Recommendations Regarding Inspection of Residential Electric-Wiring System

Discussion

The Electrical Safety Code requires that all electric equipment sold or installed in the Province of Ontario be approved by the Canadian Standards Association or Ontario Hydro and be installed in a workmanlike manner. Section 94 of the Power Corporation Act delegates to Ontario Hydro the responsibility for inspecting electric installations.

Thus the Electrical Inspection Department of Ontario Hydro performs two functions: it inspects every new installation, before electric power is connected, to check that the materials and installation meet the requirements of the Electrical Safety Code, which provides the legislative outlines for inspection requirements; and it monitors the market place to check that unapproved devices are not offered for sale to the public.

The volume of new construction and the large number of connections and terminations in the residential electric system mean that an inspector cannot check every connection in a home. The usual practice is to check several connections at various locations and, if it is found that the contractor has used approved materials and the level of workmanship is acceptable, to give final approval to the installation. On the other hand, where an electrical contractor is found consistently to perform below the required standards, a very thorough inspection is performed on all his installations.

If an installation is found to be in violation of the Electrical Safety Code, the inspector should issue a deficiency notice and the inspection should not be finalized until the violations are corrected. The Electrical Safety Code provides that the electric supply shall not be connected until the installation conforms with the Code and that the electric supply may be disconnected in any case where defects are not remedied.

From the evidence presented to the Commission, it appears that the inspection procedure for a new installation is primarily visual and rather rudimentary. The only tests routinely performed are checks for the polarity and voltage of the system. Such inspections are inadequate to insure that the Code is not being violated in terms of maximum permissible impedances, use of unapproved materials and devices, and factors related to workmanship. Particularly, there is normally no interference with the installation to check for tightness of binding-head screws. Inspections have been limited in this manner because of the pressure of work and the concern of some inspectors that a contractor could deny responsiblity for any subsequent defect.

The visual inspection of an electric system does not appear to be adequate for detecting a number of the known workmanship defects on connections, particularly insufficiently tightened screws to which aluminum wiring is particularly sensitive.

The Electrical Safety Code does not set out detailed requirements for the installation of aluminum residential systems. The provisions of Rule 12-118, "Termination and Splicing of Aluminum Conductors," include only general considerations, such as cleaning the wire, and the formation of the loop around the screws or terminations. The draft revisions for the next edition of the Electrical Safety Code recommend torque levels necessary for making a sound connection. Torque level may be tested with a special type of screwdriver. An alternative is the use of spring washers which enable tightness to be inspected visually. Some manufacturers have recommended the regular use of spring washers with aluminum wiring.

a. Conclusion. A residential aluminum-wired electric system appears to be less tolerant of poor workmanship than a copper-wired system. Currently the inspection procedure followed for the two materials is similar, whereas it would seem desirable that a more thorough inspection be required for aluminum systems.

Recommendation 19

Future revision of the Electrical Safety Code should incorporate either a design requirement that will make possible easy inspection of the tightness of binding-head screws, or a test for determining the tightness of these screws at the time of inspection.

b.   Conclusion. The adequacy of the overall wiring-system design to meet the increasing demands put upon it by modern household electric appliances does not appear to be a concern during inspection. Ontario Hydro, in their submission to the Commission, suggested that a systems approach be adopted in evaluating residential wiring. This appears to be a sensible proposal.

Recommendation 20

Ontario Hydro should develop a comprehensive systems approach to electric inspection, which should be codified as a regulation under the Electrical Safety Code. Such an approach to inspection should give due regard to the following:
  1. That the Electrical Safety Code is not violated, particularly with respect to maximum-permissible circuit impedances.
  2. That specific techniques are developed to check the workmanship of installation.
  3. That specific techniques are developed to check that the overall wiring system is designed adequately for present-day usage and for coping with developing household electric needs.
  4. That the wiring diagram (see Recommendation 12) should be checked for accuracy.

Discussion

Ontario Hydro requires that their inspectors be qualified as journeyman electricians with several years of field experience. A short period of training is provided when the inspector is first hired, but there is no programme of further training to keep inspectors up to date about technological changes and to acquaint them with new devices, bulletins, methods, and equipment.

Good inspection of an electric system appears to be particularly important for insuring that an aluminum-wired system has been properly installed.

a.   Conclusion. The role of the inspector is critical in the installation procedure and it would seem that adequate training and updating should be provided for every inspector.

Recommendation 21

The initial training period for new inspectors should be extended to include a more comprehensive review of the Electrical Safety Code and the inspection procedures necessary to detect violations of provisions of the Code. A programme of periodic updating should be instituted for all inspectors to insure that they are familiar with technological and technical changes in the industry and with changes in the Electrical Safety Code requirements.

Discussion

No doubt practical considerations and the need to be familiar with the local situation have led to the arrangement whereby Ontario Hydro inspectors report and obtain their instructions in some matters from the Manager of the Electrical Inspection Department and in others from the regional managers, but it appears that the present system makes it difficult to transfer inspectors freely about the province and to insure that all inspectors operate in the same way. To do so will be particularly important if a toll-free telephone system is instituted throughout the province.

a.   Conclusion. While the Commission gained a favourable impression of their ability and initiative, it seems that Ontario Hydro inspectors had too much to do at some times in some places. A more flexible system of employing them might ease this problem.

Recommendation 22

Consideration should be given to the possibility of transferring additional inspectors to regions where there is an excess of work and to insuring that inspectors operate in a uniform manner

throughout the province. Some strengthening of the position of the Manager of the Electrical Inspection Department of Ontario Hydro should be considered.

Discussion
Ontario Hydro, from time to time, issues *Electrical Bulletins* to augment provisions of the existing Ontario Electrical Safety Code. These bulletins are sent to most electrical contractors and electricians in the province. It appears that a new edition of the Code does not always incorporate the contents of all of the previously issued bulletins. Since the electricians do not always carry the current bulletins with them, this practice can lead to confusion and should be modified.

a. *Conclusion.* All *Electrical Bulletins* which have not been withdrawn or superseded should be incorporated in the next edition of the Code.

Recommendation 23
When a new edition of the Electrical Safety Code is adopted by the Government of Ontario, Ontario Hydro should insure that *Electrical Bulletins* that have not been withdrawn or superseded be incorporated into the new edition of the Code.

Discussion
If within six months from the date of final inspection a particular installation is found to be in violation of the Ontario Electrical Safety Code, Ontario Hydro has the legal power to demand corrective action. However, the period of six months is insufficient since many new residential units may not be occupied in this period and, in any case, the problems which arise from defective materials or installation of residential wiring systems often do not manifest themselves for some time after the system has been in use.

a. *Conclusion.* The present time limit within which Ontario Hydro may require corrective action in regard to a faulty wiring system is inadequate.

Recommendation 24
The Ontario Power Corporation Act should be amended to extend to two years (instead of six months) Ontario Hydro's powers to demand corrective action when a particular installation does not meet the Electrical Safety Code requirements.

b. *Conclusion.* In monitoring and tracing these problems, it would be useful if Ontario Hydro retained inspection forms for several years after the completion of the work on a particular installation.

Recommendation 25
The inspection records of Ontario Hydro should be retained for a period of ten years after the final inspection of a particular installation has been completed.

Discussion
It appears that an inspection of electric systems only in new construction for residential buildings does not monitor adequately the condition of the system over its expected life. However, the costs and administrative difficulties which would be involved in undertaking annual inspections would be prohibitive.

Householders often modify and augment the wiring system in their homes without obtaining a permit from Ontario Hydro and without the benefit of an electrical inspection after the alterations have been made. Strictly speaking, this practice is illegal but Ontario Hydro has no way of determining in how many instances this happens and how many such installations are actually in violation of the safety provisions of the Electrical Safety Code. In the case of new devices and technologies (e.g., aluminum wiring), which require special installation procedures, the practice of illegally modifying and augmenting residential wiring systems can lead to serious hazards.

Since the present legislation is ineffective and difficult to police, other means should be used to safeguard householders from these dangers. One method is to advertise the possible hazards while another is to use a toll-free telephone service to encourage householders to obtain advice and permits from Ontario Hydro before embarking on wiring-system modifications in their homes. A third method could be to inspect a house whenever it is sold.

a. Conclusion. Since the original wiring, which is inspected when a house is built, may deteriorate or be modified and since annual inspections are not practical, an inspection of homes on resale would encourage householders to obtain permits and advice when they wish to modify the wiring. This practice should also protect new home-owners from being involved in costly electric-wiring-modification programmes should the wiring system be deemed inadequate for any reason.

Recommendation 26
There should be a requirement that, at the time that a residential building is resold, Ontario Hydro inspect the electric system before the local electrical utility transfers the electric service to the new owners.

Discussion
Both the Electrical Inspection Department of Ontario Hydro and the Canadian Standards Association monitor the sale of electric products to control the sale and use of unapproved devices and equipment in Ontario. However, the volume of the wholesale and retail sales of these products is so large that to carry out this task completely is nearly impossible.
Evidence was presented to the Commission that some wiring devices — which are legal in other jurisdictions, particularly in the United States — have never been authorized for sale in Ontario, that an undetermined number of such devices have on occasion been marked by the manufacturers as though they were approved for use and offered for sale in Ontario, and that some of these unauthorized devices are susceptible to failure.

a. Conclusion. Ontario Hydro does have legal powers under the Power Corporation Act to forbid the sale of unapproved electric products and to order their removal from vendors' shelves. However, the only sanction available to Ontario Hydro to enforce the regulations is prosecution in the Provincial Court, which can result in the levying of a fine. Such limited powers appear to be inadequate to safeguard public interest, and additional powers to issue injunctions may be warranted.

Recommendation 27
Ontario Hydro and Canadian Standards Association should jointly improve their system of checking that unapproved electric equipment and devices are not being sold or installed in Ontario.

Recommendation 28
Ontario Hydro should have injunctive power to prevent the sale and distribution and to order removal of unapproved electric equipment and devices from distributors' shelves.

Discussion
In the retail business, wiring devices and components are often sold in open bins. This is particularly true of devices too small to be packaged individually and to carry instructions regarding their use. As a result, manufacturers' installation and usage instructions are not always available to the consumer at the point of sale. This is generally unsatisfactory and becomes critical when Ontario Hydro and the Canadian Standards Association have approved a device for limited applications only.

a. Conclusion. Consumers are not always informed of the instructions and limitations for use of the devices and components which they purchase.

Recommendation 29
The Electrical and Electronic Manufacturers Association of Canada, the Canadian Standards Association, and Ontario Hydro should insure that the retailer provide the purchaser of a device or component with full information from the manufacturers, on either the device or the package in which a device is sold by the retailer, or that the information be prominently displayed beside the bins at the point of sale.

2.14   Recommendations Regarding Warranties

Discussion

Questions concerning the acceptable life of a wiring system were raised during the Commission's hearings. Clearly, a householder should not be expected to renew his complete wiring system every few years. A large number, certainly the majority, of homes wired with copper have wiring systems that have lasted over twenty-five years. Similarly, many aluminum-wiring systems have lasted over ten years and are still functioning satisfactorily, but there is little experience for longer periods.

Understandably, heavily used wiring devices, such as receptacles in a kitchen, may not last as long as the wiring system as a whole. However, even in these cases, frequent replacements are not desirable. Because of the competitive nature of the residential wiring industry, device manufacturers lack the incentive to improve reliability, because this would probably increase the cost and hence the risk that their products would be less competitive. Household wiring devices are designed by the manufacturers to pass the minimum safety standards of the Canadian Standards Association. Durability or long-term reliability, as such, is not a paramount consideration in design. Any improvement in design or installation practice, to be acceptable, must apply across the board and be incorporated into the relevant industry standards and the Electrical Safety Code. For simple economic reasons, in a highly competitive industry, it is unreasonable to expect a manufacturer or contractor to make his product or installation significantly more durable than that of his competitors, unless the regulatory agencies, Ontario Hydro and the Canadian Standards Association, require improvements by the whole industry. To say this is not to be critical, but to recognize the realities of the situation.

The Legislature enacted The Ontario New Home Warranties Plan Act, 1976, which became effective on the 31st of December, 1976. It applies only to new construction of single-family, duplex, and similar residential buildings completed since the passing of the legislation. The plan is administered by the Housing and Urban Development Association of Canada (HUDAC).

The definition of an owner of a home under the Act includes the original purchaser and his successors in title and thereby provides for flow-through of the warranty to subsequent purchasers.

The plan provides a warranty for the home-owner whereby the builder is required to repair all defects in material or workmanship for a period of one year. Major structural defects are covered for a further period of four years during which the home-owner is entitled to make a claim against the plan. The outline of major structural defects does not appear to include the electric wiring system. This effectively results in a warranty period of one year for wiring defects, and Ontario Hydro's power to order remedial action, when residential wiring is found deficient, is limited to six months. Many homes are not sold or occupied until more than the first six months after the final inspection by Ontario Hydro. The evidence presented during the Commission's hearings indicates that it is sometimes three or four years before failures with pre-CO/ALR devices become apparent.

The Commission heard a great deal of evidence concerning the level and quality of electrical workmanship in the Ontario household-wiring industry. It is evident that competition is fierce at the subtrade level in the Ontario building industry. Cost savings of a few dollars per house for a wiring installation can be crucial in gaining a contract. The pressure of competition sometimes has forced electrical contractors to employ non-certified electrical workmen and to adopt other cost-saving practices. These include piece-work subcontracts and the use of pump screwdrivers. Both of these practices tend to produce fast and shoddy workmanship and a failure to tighten binding-head screws. In the past the Electrical Safety Code gave no specific guidance to electricians on workmanship requirements for either copper- or aluminum-wiring terminations. This omission now has been partially rectified in the 1978 edition of the Code, which stipulates a

torque of 12 lb-in for binding-head screw connections. However, no such guidance is given for pigtail connections.

The inspection procedure during the course of construction does not seem to control adequately the calibre of workmanship. This may be due to the large volume of work and to the complex nature of the wiring system. Electrical inspectors and others have testified that it is very difficult to check in the field the quality of workmanship at each wiring termination.

The diversity of training received by electricians currently practising in Ontario means that uniformity of technique and quality is not readily achievable.

The relatively low cost of electric-system components and the high labour cost of electrical contractors encourage unqualified home-owners to tamper with the system.

There are a number of characteristics of residential electric circuits that indicate the need for increased consumer protection. Although some of these characteristics apply to copper-wired circuits, such safeguards are particularly desirable in the case of aluminum-wired circuits because the quality of workmanship necessary for the optimal performance of an aluminum-wired system appears to be higher than that required for a comparable copper-wired system. There is no evidence to suggest that the quality of workmanship is always poorer for aluminum-wiring installations compared to that with copper wiring, but poor workmanship sometimes goes with aluminum wiring because a major reason for the use of aluminum has been the desire to save a little money.

A large number of homes in Ontario with aluminum wiring are not covered by the HUDAC plan since they were constructed prior to the passing of the Home Warranties Plan Act. The consumer legislation and common law of Ontario may not provide a means of rectifying defects in the wiring system of these homes as there is no privity of contract between the home-owner and the electrical contractor. In many cases home-owners do not even know the name of the particular electrical contractor. The home-owner who has repaired or replaced portions of the electric system may be able to obtain redress through the provisions of his contract with the builder.

a.   Conclusion. The Commission is aware of the difficulties involved in making effective any warranty to consumers on goods and services. Notwithstanding these difficulties and bearing in mind the substantial investment that a house represents to a householder, it is important that the Government of Ontario, in conjunction with the Ontario building industry, examine ways and means of affording a greater degree of protection to prospective home buyers in Ontario against faulty and poor workmanship and the use of non-certified or poor-quality products.

For the future, a comprehensive home-warranty plan potentially provides a means of guaranteeing a satisfactory minimum level of workmanship. The Ontario New Home Warranties Plan Act, as it is at present, provides adequate protection to the new home-owner as regards those defects of material or workmanship that are included as "major structural defects" under the statute. A considerable number of the problems associated with the inferior materials or installation of the electric system are not likely to manifest themselves for some time. A warranty period of one year would seem to provide inadequate protection for the average home-owner because the period until problems surface may exceed one year.

Recommendation 30

The Ontario New Home Warranties Plan Act, 1976 should be amended to provide that the electric system is a major component of the home and therefore should be covered by the five-year warranty period. Notwithstanding the difficulties inherent in making a warranty system effective, the Government of Ontario is urged to consider the establishment of a more comprehensive system of home warranties. Any such warranty should cover the residential wiring system for a period of five years.

b.   Conclusion. In spite of these various matters of concern, most of the aluminum-wired homes built prior to 1976 do not appear to be reporting defects or failures. Because most of the aluminum-wired houses in Ontario were built more than five years ago, they would not be covered by retroactive extension of the warranty. Since 1974 the number of such homes has rapidly declined and it does not seem necessary, therefore, to extend the warranty programme to cover these homes retroactively. Recommendations 2 to 7 propose methods of alerting home-owners to possible dangers and of advising them upon corrective action.

Recommendation 31

Warranties need not be applied retroactively, but the Government of Ontario should insure that a programme of public education is undertaken. The programme would include the distribution of information advising the owner of a home wired with aluminum to consider having the electric system inspected for defects in material and workmanship. (See also Recommendation 41.)

c. *Conclusion.* Operational experience with the HUDAC warranty indicates that there are many unsatisfied claims, owing largely to the fragmented nature of the building industry and the rather cumbersome procedure for making claims against the warranty.

Recommendation 32

The Ontario building industry should establish a fund to underwrite unsatisfied claims against the above warranties.

2.15   Recommendations Regarding Training and Licensing of Electricians in Ontario

Discussion

The training and licensing of electricians in the Province of Ontario is controlled by the Apprenticeship and Tradesmen's Qualification Act, R.S.O. 1970, Chapter 24. The Ministry of Colleges and Universities administers the trade and is responsible for training, granting of qualifications, and enforcing the statutory regulations. The Act designates the trade as a compulsorily regulated trade and every electrician is required to hold a certificate of qualification or be registered as an apprentice before he can practise his trade.

Pursuant to the provisions of the Act, the Ministry of Colleges and Universities administers the apprenticeship-training programme and, therefore, has control over the training of electricians in Ontario. The apprenticeship programme provides for both classroom instruction in the community colleges and for practical experience on the job. The Ministry produced an outline of the curriculum for apprentices that is used by the various community colleges which carry out the programme. The curriculum issued by the Ministry does not require a period of instruction covering the installation of aluminum wire in residential circuits. The choice of materials and equipment to be used by the students is left to the discretion of each college and is generally based on economic considerations. In practice the material of choice is small-gauge copper wire because of ease of use and relatively low cost. The instruction given on the installation procedure and requirements is based directly on the provisions of the Electrical Safety Code.

In addition to the classroom training provided by the community colleges, the apprentice enters into a contract with an electrical contractor who undertakes to provide the apprentice with field training. The only opportunity to control the nature of the training received on the job is through the apprenticeship contract.

All apprentices must pass a comprehensive examination before receiving a certificate of qualification which they require to practise their trade. The contents of the examination are under the control of the Ministry of Colleges and Universities.

In Ontario a large number of the electricians entering the trade come from other jurisdictions where they have already completed formal training in the trade. The diversity of training backgrounds of these electricians precludes the Ministry of Colleges and Universities from exercising detailed control over the background knowledge of each candidate. These tradesmen must take a comprehensive knowledge examination and, where applicable, demonstrate their level of practical skills. If the required knowledge and skills are demonstrated, the candidate is issued a certificate of qualification which authorizes him to practise the trade in Ontario.

Once the certificate of qualification has been issued to the electrician, it must be renewed every two years, but renewal is automatic upon the payment of a registration fee. There are no requalification examinations required once the electrician begins to practise the trade. Upgrading programmes are available on a volunteer basis from the community colleges, trade unions, and trade associations. The content of the courses depends largely on the requirements and interests of the agency sponsoring the programme. Most of the technological and technical changes are learned on the job.

a.   Conclusion. The Ministry of Colleges and Universities, as the responsible government body, is in a position to insure that the electricians trained in Ontario receive adequate instruction in the installation of aluminum wire in residential electric circuits. At the present time, the curriculum of the training programme for apprentice electricians does not require that instruction be given in the proper installation of aluminum wire in residential wiring systems.

Recommendation 33

Consideration should be given to amending the curriculum prepared by the Ministry of Col-

leges and Universities, under the provisions of the Apprenticeship and Tradesmen's Qualifications Act, to include instruction in proper installation requirements for aluminum, as well as for copper, residential wiring systems. Differences in properties and behaviour of the two metals should be stressed and the necessity for good workmanship in aluminum-wired circuits emphasized.

b. *Conclusion.* A fairly large number of electricians who practise their trade in Ontario enter the province from other jurisdictions. The only point at which control may be exercised over the competence of these electricians is in the administration of the comprehensive examination and the demonstration-of-skills test.

Recommendation 34

Consideration should be given to including questions on the comprehensive examination to insure that the tradesman has an adequate knowledge of the techniques required to install aluminum wire. It is recognized that the basic installation techniques are similar for both copper and aluminum wire, but the apparent need for greater care during the installation of aluminum wire makes it desirable that all electricians have an understanding of the differences in the use of the two materials.

c. *Conclusion.* The nature of the electrical industry is such that technical changes are occurring continually. As new components are introduced, it is desirable that instructions for their proper use be disseminated widely. The cost and administrative difficulties which would accompany a compulsory retraining programme in the use of aluminum wiring precludes such a venture, nor does it appear to be necessary.

Recommendation 35

A programme of training for practising electricians in the use of aluminum wire for residential circuits is impractical and unnecessary. The trade can be adequately informed of installation requirements of aluminum wire by notification of Electrical Safety Code provisions.

2.16   Recommendations Regarding Recall of Equipment

Discussion

The power to regulate the electrical industry is delegated to Ontario Hydro by Section 94 of the Power Corporation Act. The Electrical Safety Code — which provides that no person shall use electric equipment of a regularly manufactured line unless it is approved by the Canadian Standards Association in accordance with the Code — empowers Ontario Hydro to control the sale and use of all electric equipment in Ontario. The power to enforce these provisions arises because it is an offence for anyone to fail to comply with any section of the Power Corporation Act or the Electrical Safety Code.

The sanctions that Ontario Hydro may apply when unapproved electric equipment has been used are limited. It is a Summary Conviction Offence to fail to comply with a regulation passed under the Power Corporation Act and, if convicted, the party is liable for a penalty of not less than $25.00 and no more than $500.00 for each offence.

Once electric equipment has been installed, Ontario Hydro has some means to accomplish the removal of unapproved equipment. Section 2-012 of the Electrical Safety Code states that electric installations cannot be connected to the service until the installation has been inspected and found to be in compliance with the provisions of the Code. Section 2-018 of the Electrical Safety Code requires a contractor to remedy any defect and replace any equipment that is not approved; where the contractor fails to comply with the notice under this Section, Ontario Hydro may disconnect the electric supply.

The Canadian Standards Association has some control over the sale of unapproved electric products. In cases where an unapproved product is marked with the Canadian Standards Association certification mark, the Association can bring action for wrongful use of the mark. If the manufacturer involved has submitted products to the Canadian Standards Association for approval, the company is subject to a service agreement which may be cancelled upon failure to comply with the regulations. The service agreement is necessary to obtain and maintain certification of any electric equipment.

Products that are decertified by the Canadian Standards Association are subject to the same provisions as those that were never approved. In practice, the majority of decertifications occur because a product has become obsolete rather than a subject of immediate safety concern. The manufacturer may be requested to recall decertified products from its distributors. As soon as the product is decertified, the relevant inspection authorities are notified and the product cannot be used in new installations. Generally no attempt is made to notify the consumer of the product's decertification.

It appears that the sale and installation of unapproved and decertified equipment normally do not occur on a large scale. There have been instances, notably the steel-screw receptacle, where unapproved products in considerable numbers were installed in Ontario homes. The Electrical Inspection Department of Ontario Hydro and Canadian Standards Association both monitor the sale of products to try to control the use of unapproved equipment but the volume of electric-equipment sales in Ontario is so large as to make this task nearly impossible.

a.   Conclusion. Ontario Hydro has been given the power by the Power Corporation Act to forbid the sale of unapproved electric equipment and to order its removal from sale and stock shelves. The only sanction available to enforce the regulations is prosecution in the Provincial Court, which can result in the levying of a fine. Such limited powers do not appear to be an effective measure for controlling the sale of unapproved products, and Recommendation 28 suggests remedial action that should be taken.

Once unapproved equipment has been installed in a home, Ontario Hydro can enforce an order

for removal by refusing to connect, or by disconnecting, the electric supply to the residence. Either of these sanctions is inappropriate in the residential building market because the home-owner, who in most cases is an innocent party, would be greatly inconvenienced. The provisions for prosecution before the Provincial Court are still applicable provided that the limitation period for prosecution has not expired.

Recommendation 36

In addition to the existing powers, Ontario Hydro should be given the power to require that the builder or electrical contractor remove all unapproved equipment or materials. Where there is a failure to comply with a notice to remove within a reasonable time, Ontario Hydro should have the authority to remove and replace the equipment at the expense of the builder or electrical contractor. The limitation period should extend for two years after the initial occupation of the home.

b.   Conclusion. The nature of the housing industry appears to make it impossible to undertake a programme of identifying and replacing unapproved equipment in existing installations. Unlike automobiles, houses are not closely standardized and no records are kept of precise components in them. The majority of Ontario houses with aluminum wiring were built more than five years ago so that all warranties on them have expired.

There is good evidence that with binding-head screws a tight connection may last even with inferior devices. In any case, warning signs usually occur before a failure. Most home-owners who have experienced these signs have already taken corrective steps, as the sale in Canada of about 1,500,000 CO/ALR receptacles shows.

Throughout the hearings much evidence showed that the problems and failures that had plagued aluminum wiring had been reduced so greatly that few new cases had occurred. Nevertheless, there may remain a quantity of unapproved materials or instances of poor workmanship which have not been corrected. Recommendation 5 and others deal with these situations.

2.17   Statistics on Fires of Electric Origin in Ontario

Discussion

Although fires of electric origin in residential units are in the minority, the increasing trend to the use of high-power domestic appliances, the introduction of new technologies which are more susceptible to poor workmanship, and the misuse of wiring systems may alter the relative incidence of fires of electric origin. To keep a close watch on this possibility, it is essential that the procedures for collecting and classifying field data used by the Ontario Fire Marshal's Office, Ontario Hydro, and the Canadian Standards Association should be enhanced and made more consistent throughout the province.

The Fire Marshal of Ontario is to be congratulated upon the first issue of an annual report entitled *1976 Fire Losses in Ontario* (Exhibit 198). In this first issue some difficulties were encountered, but it is understood that these can be overcome and that changes are being made in the classification of fires.

a.   Conclusion. The need for more precise statistics on the origin of fires in Ontario has been recognized. There is a need to instruct fire departments, the Fire Marshal, and Ontario Hydro inspectors of the importance of collecting data in a precise and uniform manner which is consistent throughout Ontario.

Recommendation 37

The Ontario Fire Marshal's Office should review with all fire departments in the province and other appropriate agencies, methods of recording the details of electric fires and incidents to insure that reports are complete and uniform. Reports should always state whether copper or aluminum wiring or both were used in the branch circuits, regardless of whether or not the wiring is regarded as a contributing factor.

Recommendation 38

The Ontario Fire Marshal's Office and Ontario Hydro should establish a procedure whereby all local fire departments call an inspector from Ontario Hydro to the scene of any fire suspected to be of electric origin.

Recommendation 39

Ontario Hydro, in conjunction with the Canadian Standards Association, should improve and enhance their systems of information collection and retrieval. These systems should include field data on the reliability and safety of aluminum- and copper-wired dwelling units. Inspection, reinspection, and electric-incident and -fire reports could form the bases of the revised information-gathering system. Ontario Hydro and Canadian Standards Association should consider which parts of this material would be useful to the public and establish means of disseminating useful information.

2.18 Setting Electric Standards

Discussion

As mentioned already, the chief preoccupation of Ontario Hydro and the Canadian Standards Association is to insure safety in the use of electricity in a home. The present device-certification standards do not adequately test for long-term reliable performance. The attitude of the manufacturing industry, quite understandably, has been to let the buyer decide the level of reliability for which he is prepared to pay. Unfortunately, the home-owner, who is the end user, has only an indirect choice as he must purchase the house as a unit. However, too low a level of reliability does pose a safety hazard and Ontario Hydro and the Canadian Standards Association have to provide to the industry some guidance about a minimum acceptable level of reliability in addition to safety.

To determine an acceptable level of reliability, new laboratory tests will have to be devised. These tests will have to bear some relationship to the expected level of workmanship and to the anticipated use of a wiring system during its life. Temperature-cycling tests with minimal conductor disturbance (e.g., in CO/ALR tests) do not appear to go far enough in accelerating failure mechanisms that may give rise to overheating in the field. The current knowledge of field failure mechanisms of residential wiring devices, whether of copper or of aluminum, is also woefully inadequate and additional laboratory and field investigations are necessary.

The Electrical and Electronic Manufacturers Association of Canada outlined in their evidence a programme of improvement for residential wiring devices. This programme is commendable. However, device-development programmes must go hand in hand with improved certification testing for reliability by the Canadian Standards Association.

From the evidence before the Commission, it appears that the bulk of the supporting laboratory data on any device submitted for approval to the Canadian Standards Association comes from the manufacturer who is seeking approval. This is understandable and perhaps acceptable under normal circumstances. However, when major or significant technological changes are imminent in the residential wiring components or installation practices, or when the complete wiring system is in need of redesign or re-appraisal, the Canadian Standards Association should have access to results of independent investigations and also should have its own resources to conduct or commission independent investigations. The latter aspect is important in the standard-setting process. To some extent, the W.P. Dobson Research Laboratory of Ontario Hydro and the Canadian Electrical Association have performed this function. However, some source of additional funding is needed for the Standards Division of the Canadian Standards Association, as Recommendation 18 has suggested.

a.   Conclusion. Since the Standards Council of Canada is the overall statutory body concerned with electrical standards, and since experience in Ontario with aluminum wiring is relevant to that in other jurisdictions in Canada, the findings of this Commission should be communicated to the Standards Council of Canada.

Recommendation 40

The Standards Council of Canada should be informed of the findings of this Commission.

2.19   Recommendations Regarding Public Education

Discussion

From the evidence it is clear that home-owners have woefully inadequate knowledge of their wiring system, of the limitations to its use and misuse, and of the nature of the safety problems that could occur with aluminum or copper wiring. This is cause for considerable concern, since the use of electricity in homes continues to increase and there must be some very old residential-wiring installations in Ontario. Ontario Hydro's experience with the hot line in Brampton confirms this situation, and shows that many members of the public do not know what to do when confronted with symptoms of electric problems in a home.

a.   Conclusion. A programme of continuing public education about the safe use of electricity in a home should be undertaken by the various relevant public agencies and private organizations in Ontario.

Recommendation 41

Ontario Hydro, in conjunction with the Canadian Standards Association, local electrical utilities, the Electrical and Electronic Manufacturers Association of Canada, and the Electrical Contractors Association of Ontario, should develop a programme of public education on safety of electric installations in homes. These organizations should endeavour to interest the building industry in the extension of this programme to cover all aspects of home safety.

Recommendation 42

The findings of this Commission, since they are based upon a thorough inquiry among all those concerned with electrical safety in Ontario, should be publicized widely through the general and technical press and by the radio and television stations.
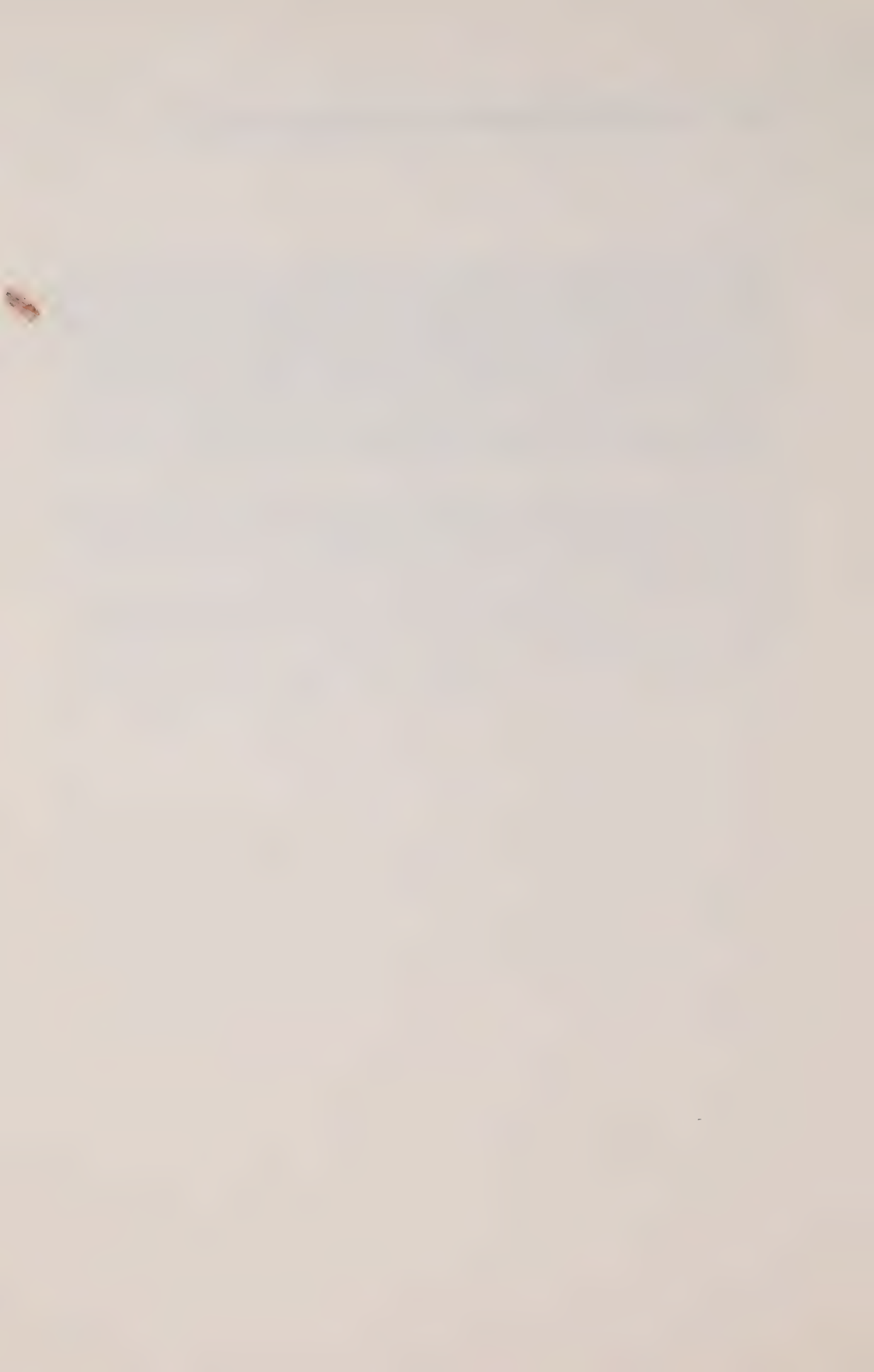
2.20 Recommendation for a Future Review

Discussion

As already noted, this Commission of Inquiry on Aluminum Wiring heard evidence on how the residential wiring system has grown over the past several decades and on how the utilization of electricity in Ontario residences has increased and may continue to increase, which, in turn, places additional strain upon branch-circuit wiring. In the interests of concluding this public inquiry without undue delay and to avoid a very large expenditure which circumstances did not appear to warrant, it was decided to refrain from conducting an exhaustive field survey in Ontario to determine accurately the extent of electric-wiring problems in Ontario homes. The Commission found no evidence to support the alarmist view that aluminum wiring is a "time bomb" which would eventually cause increasing and widespread damage. On the contrary, the steps taken by various organizations have already improved safety and reliability — but no system is entirely safe.

a. Conclusion. A continuing overview and watch are desirable to insure that improvements and modifications, already made by the various regulatory agencies or recommended in this report, to aluminum-wiring systems in particular and to the overall wiring system in general are having the desired effect of improving the safety and reliability in Ontario homes.

Recommendation 43

The Government of Ontario, through its Ministries of Housing, Consumer and Commercial Relations, Energy, and Attorney General, should review the residential aluminum-wiring situation in Ontario not later than 1983.